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FIELD TEST SECTIONS ON EXPANSIVE SOIL.(U)
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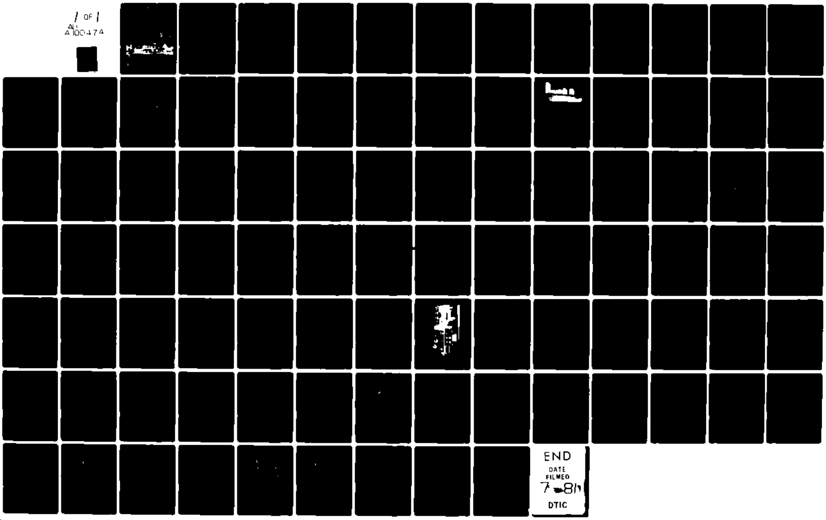

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TECHNICAL REPORT GL-81-4

FIELD TEST SECTIONS ON EXPANSIVE SOIL

by

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May 1981

Final Report

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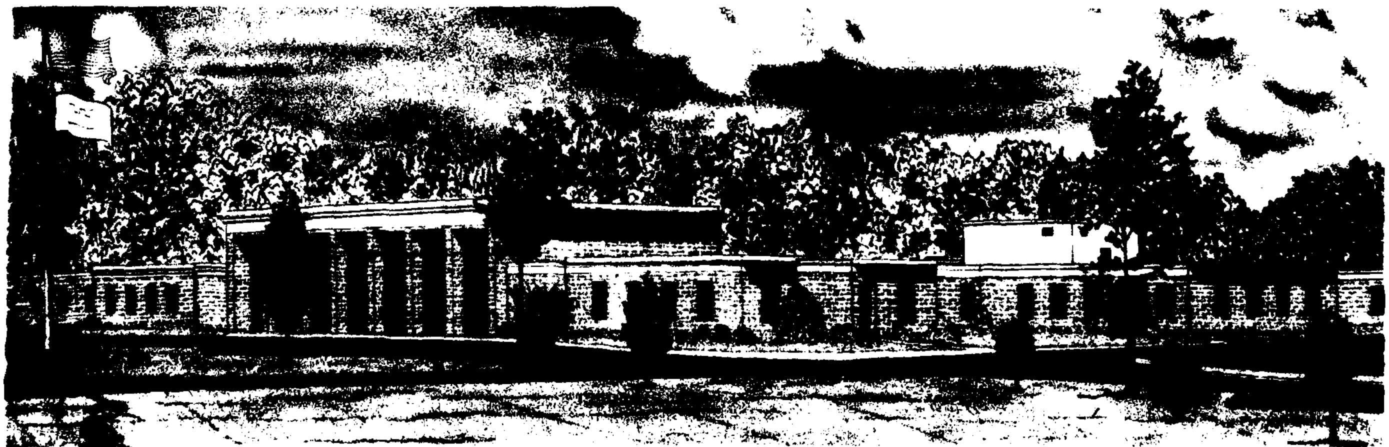

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This report presents results of field observations at three test sections consisting of 100-ft-square moisture barriers over the surface of in situ swelling soils located near Clinton, Miss.; Lackland Air Force Base, Tex.; and Fort Carson, Colo. Results from more than 5 years of observations show that long-term or progressive heave builds up over many years and tends to be erratic, with most progressive heave accumulating toward the center of the sections. Seasonal or short-term cyclic heave was substantial in the semiarid climate of Lackland and was most noticeable within 10 ft inside and outside (Continued)

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20. ABSTRACT (Continued)

of the edge of the 100-ft-square sections. The cyclic seasonal heave exceeded the long-term progressive heave at Lackland. Seasonal heave was not significant at the Clinton test section where a nonswelling overburden overlaid the swelling soil. The amount of heave was strongly influenced by the depth to the water table.

The equilibrium pore water pressure profiles obtained for soils taken from beneath the test sections are consistent with pressures between saturated (zero pore water pressure) and negative hydrostatic above the original groundwater level. The large magnitude of the osmotic component of suction observed at the Fort Carson test section had little effect on heave, even after 7 years of observations.

Predictions of heave based on a saturated equilibrium moisture profile using suctions measured with thermocouple psychrometers and filter paper provide reasonable overestimates compared to those actually observed at the three test sections.

PREFACE

This report was prepared under RDT&E Work Unit AT40/E0/004, "Foundations on Swelling Soils," sponsored by the Office, Chief of Engineers, U. S. Army. The investigation on which this report is based was conducted during the period October 1968-August 1980.

The report was prepared by Dr. Lawrence D. Johnson, Research Group (RG), Soil Mechanics Division (SMD), Geotechnical Laboratory (GL), U. S. Army Engineer Waterways Experiment Station (WES), under the general supervision of Mr. Clifford L. McAnear, Chief, SMD, and Mr. James P. Sale, Chief, GL. Dr. Paul F. Hadala, Acting Assistant Chief, GL; Mr. W. R. Stroman, Foundations and Materials Branch, U. S. Army Engineer District, Fort Worth; Mr. Gerald B. Mitchell, Chief, Engineering Group, SMD; and Dr. Edward B. Perry, RG, SMD, reviewed the report.

The cooperation of Mississippi College, Clinton, Miss.; Lackland Air Force Base, Tex.; and Fort Carson, Colo., in providing sites for the field test sections is much appreciated.

Director of WES during the preparation of this report was COL N. P. Conover, CE. Technical Director was Mr. F. R. Brown

CONTENTS

CONVERSION FACTORS, INCH-POUND TO METRIC (SI) UNITS OF MEASUREMENT

Inch-pound units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
inches	2.54	centimetres
tons (force) per square foot	95.76052	kilopascals
pints (U. S. fluid)	0.47318	litres

FIELD TEST SECTIONS ON EXPANSIVE SOIL

PART I: INTRODUCTION

Background

1. The swell and shrinkage of expansive soil cause extensive damage to numerous structures such as foundations and walls of retaining walls, canal and reservoir linings, pavements, and highways. The types of damage include distortion and cracking of pavements and on-grade floor slabs; cracks in grade beams, walls, and drilled shafts; jammed or misaligned doors and windows; and failure of concrete blocks or plinths supporting grade beams. Lateral forces may buckle basement and retaining walls, particularly in overconsolidated soil. Damages are widely observed throughout much of the Western, Central, and Southern areas of the continental United States as well as many other areas of the world. Annual costs of these damages in the United States are conservatively estimated to exceed $1 billion and probably approach $2 billion or more (Jones and Holtz 1973, Snethen 1979).

2. Damages to structures are caused by differential movement of the foundation soil. Differential movements redistribute the structural loads and cause large changes in moments and shears not accounted for in design. These in time cause changes in stress which result in cracking and/or undesirable relative deformations in the structure.

3. The leading cause of differential movement is nonuniform changes in soil moisture attributed to changes in the field environment and to usage requirements of the structure. Spatially nonuniform moisture changes occur from local concentrations of water from surface ponding, broken water and sewer lines, leaky faucets, defective drains, defective rain gutters and downspouts, local transpiration of moisture from nearby trees, diffusion of moisture away from heat sources such as furnaces, and from the geometry of the structure itself since the

foundation is often a very good moisture barrier. Differential movement is also aggravated by lateral variations or discontinuities in the soil profile such as, for example, transitions between the pervious Austin chalk and relatively impervious expansive soil of the Eagle Ford, Taylor, or Woodbine formations near Dallas, Tex.

4. Heaving is often erratic, occurring over periods of 4 or more years. It sometimes is concentrated near one or more sides of the structure. Sometimes a mushroom or dome-shaped pattern of greatest movement toward the center of the structure occurs. This is commonly associated with a reduction of the natural evapotranspiration under the structure. Seasonal expansion and contraction can be superimposed on the long-term heave near the perimeter of the structure. Seasonal movement is aggravated by poor drainage and large variations in the climate such as the frequency and amount of rainfall. Edge effects may extend inward 5 to 10 ft* and become less significant on well-drained land. Sometimes, a dish-shaped or cupping pattern may occur beneath foundations due to consolidation, drying out of surface soil from a heat source, or localized lowering of the water table.

Purpose and Scope

5. The design and construction of structures on swelling soil have been the subject of study and research for many years. Much has been learned about the behavior of structures on swelling soil, but many problems remain. One of the most significant problems is predicting total and differential soil heave that eventually accumulates at different points beneath the structure, information important to the design of the structure. Reliable predictions of heave require accurate estimates of the equilibrium or final pore water pressure profile.

6. This report presents the results of field observations accumulated from October 1968 to August 1980 at three test sections and

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* A table of factors for converting inch-pound units of measurement to metric (SI) units is presented on page 3.

updates the field observations reported previously by the author (Johnson 1978). The purpose of these field test sections is to provide data from which a reliable method may be developed to predict reasonable potential soil vertical movement for use in the design and construction of structures founded on expansive soils. The field test sections are located in Clinton, Miss.; Lackland Air Force Base, Tex.; and Fort Carson, Colo. Field observations made include climate, piezometric pore pressures, and soil heaves. The soil moisture profiles existing in the soils beneath the test sections during the summer of 1979 were determined from laboratory tests on undisturbed boring samples taken from beneath the center of the test sections. These moisture profiles are expected to be very close to the equilibrium or final profiles.

PART II: CHARACTERIZATION OF CLIMATE

7. The location and climate of the three test sections constructed for study are briefly as follows:

Test Site	Location	Climate	Elevation ft msl	Annual Rainfall in.
Clinton	Clinton, Miss.	Warm, humid	328	50
Lackland	San Antonio, Tex.	Semiarid	770	28
Fort Carson	Colorado Springs, Colo.	Semiarid	6000	17

The semiarid climates of the Lackland and Fort Carson test sections are generally more conducive to severe swelling soil problems than that at Clinton. These test sections are located in high swelling soil areas that have a history of extensive damages from heave (Snethen 1979). The climate of each test section was quantitatively characterized by the Thornthwaite moisture index.

Thornthwaite Moisture Index

8. Climate may be characterized from rainfall and temperature data by Thornthwaite's method (1948). The overall availability of moisture during the year is given by Thornthwaite's moisture index

$$MI = \frac{100S - 60D}{PE} \tag{1}$$

where

MI = Thornthwaite's moisture index

S = annual water surplus, in.

D = annual water deficiency, in.

PE = annual potential evapotranspiration, in.

The water surplus S is given more weight than the water deficiency D because the water deficiency is only partially effective in restricting the availability of moisture. Transpiration still proceeds during a drought by deeply rooted perennials.

9. The surplus and deficiency are functions of the amount of available water

$$M = C + r - pe \quad \text{for} \quad C \leq C_f \tag{2}$$

where

M = amount of available water, in.

C = amount of water stored in the soil, in.

r = rainfall for the month, in.

pe = potential evapotranspiration for the month, in.

C_f = field water capacity of the soil, in.

The field capacity C_f is the amount of readily available water that the soil can store within the root zone of vegetation. A water surplus s for a particular month will occur if rainfall exceeds the potential evaporation for the month and the amount of stored water is at the field capacity

$$s = r - pe \geq 0 \quad \text{for} \quad C = C_f \tag{3a}$$

A water deficiency d for a particular month will occur if the potential evaporation exceeds the rainfall for the month and if all of the stored water had been used

$$d = r - pe < 0 \quad \text{for} \quad C = 0 \tag{3b}$$

Summation of all of the monthly surpluses s and deficiencies d equals the annual surplus S and deficiency D, respectively.

10. The monthly potential evaporation pe is an estimate of the total possible loss of water from a sizeable field by transpiration from vegetation and evaporation from the soil with adequate water reserves and can be found by

$$pe = 0.63\left(\frac{10t}{I}\right)^a \tag{4}$$

where

t = monthly mean temperature, ^{o}C

I = heat index

a = empirical constant

The annual potential evaporation is the sum of the twelve monthly values of pe. The heat index I is the sum of twelve monthly indices i which are functions of the monthly temperature t and given by a table in Thornthwaite (1948). The constant a is a function of the heat index I and is given by

$$a = 6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 1.79 \times 10^{-2} + 0.49 \qquad (5)$$

11. Calculation of the Thornthwaite moisture index MI is a very laborious procedure if done manually. A simple graphical procedure was developed by Palmer and Havens (1958) which was used in this report. The moisture index has been shown to provide a satisfactory measure of soil moisture conditions (Russam and Coleman 1961, Richards 1966), although it is an empirical relationship between rainfall, temperature, and the potential evapotranspiration PE .

Climates at the Field Test Sections

12. All of the meteorological data for the test sections were obtained from U. S. Weather Bureau "Annual Summary" reports. The rainfall and temperature data characteristic of the three test sections were obtained from weather stations at the nearest commercial airports. The field water capacity C_f of all of the soils was assumed to be 4 in., a reasonable value for clay. Thornthwaite's moisture index was calculated over a span of several years including 2 to 4 years prior to construction of the test sections. Large, positive MI values indicate very humid, wet climates; large, negative indices indicate very dry, arid climates.

Clinton

13. The soil moisture conditions at the Clinton test section

(Figure 1) show large, positive moisture indices indicative of a very humid and wet climate. The water deficiencies indicate that the normal dry season is in the latter part of summer and ends in about October. The years from 1971 to 1977 and 1979 in particular were exceptionally wet compared to 1969 and 1978. The cover was placed in October 1969.

Lackland

14. The Lackland test section was generally exposed to a hot, semiarid climate as indicated by the negative moisture indices (Figure 2). Water deficiencies indicate that the dry season includes the summer and occasionally the spring and fall months. A relatively wet year was recorded during 1973, 1 year prior to construction of the section cover. The years since placement of the cover have been moderately dry.

Fort Carson

15. The Fort Carson test section has been exposed to the driest (and coldest) climate as is indicated by the large negative moisture indices (Figure 3). The soil has been exposed to water deficiencies during most of the year, except in late fall and winter. The driest year was recorded in 1974, 1 year following construction of the section cover.

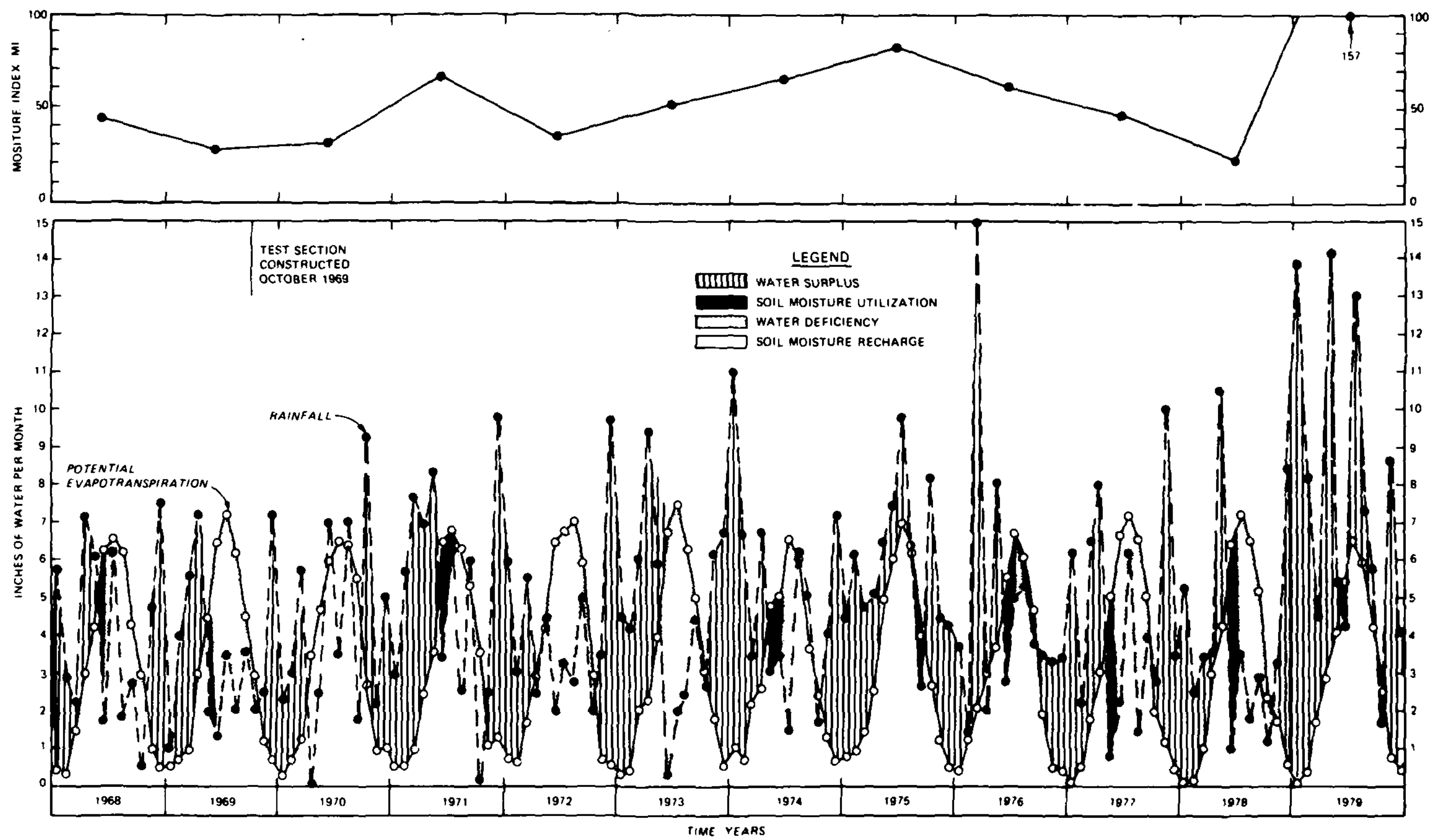


Figure 1. Thornthwaite moisture index at Clinton

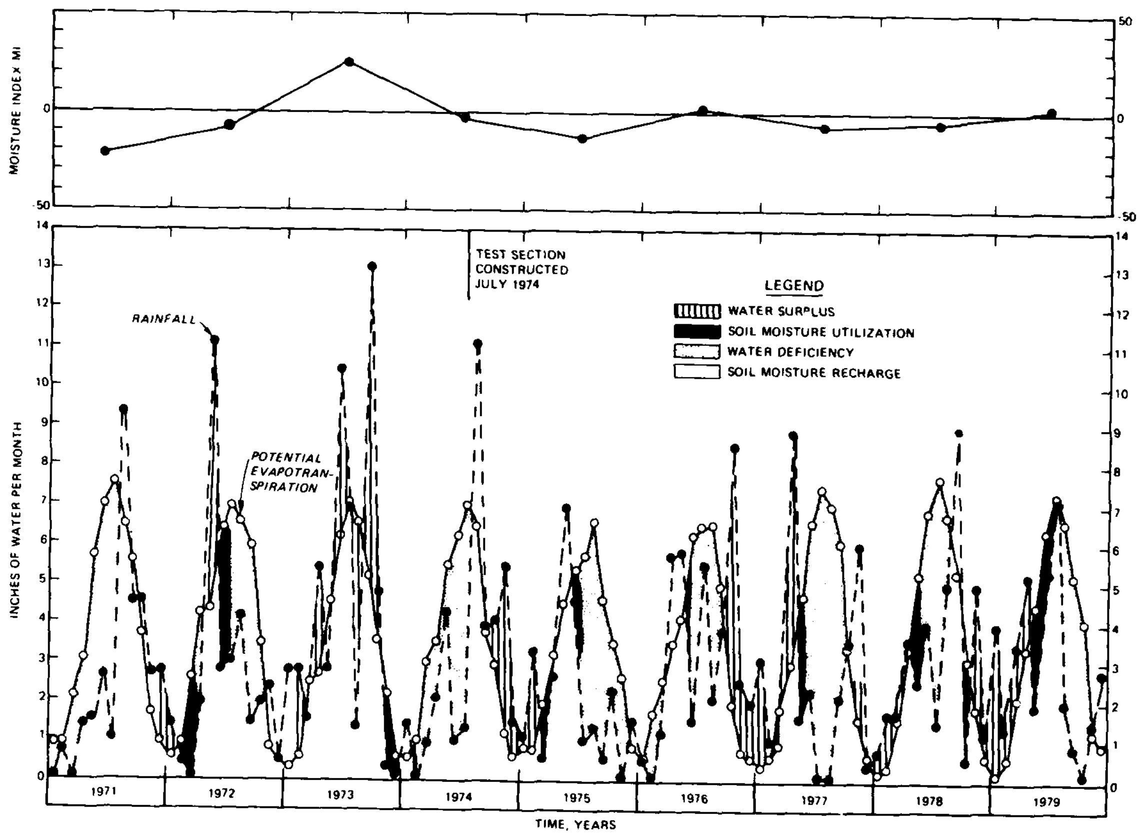


Figure 2. Thornthwaite moisture index at Lackland

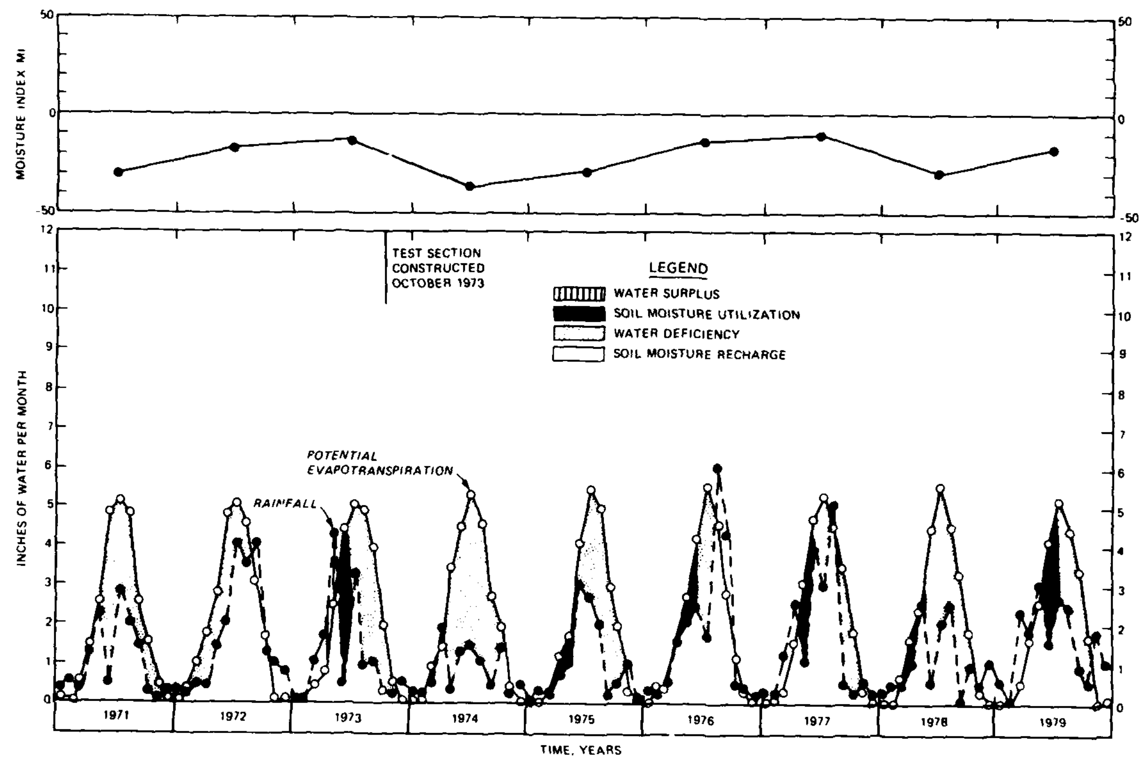


Figure 3. Thornthwaite moisture index at Fort Carson

PART III: DESCRIPTION OF TEST SECTIONS

Instrumentation

16. Test sections were constructed at the Clinton, Lackland, and Fort Carson test sites in October 1969, July 1974, and October 1973, respectively. Each was constructed of two 100-ft-square impermeable membranes separated by a 0.8-ft-thick layer of sand as shown in Figures 4-6. The covers were placed on graded level surfaces which had been stripped of up to 6 in. of topsoil and vegetation. The Lackland test section includes a drilled shaft (Figure 5) as part of an earlier investigation (Fort Worth District 1968).

17. Instrumentation includes permanent bench marks, open tube Casagrande piezometers, surface and deep heave plates, soil suction thermocouple psychrometers and temperature thermocouples (at the Clinton and Lackland test sections), and aluminum access tubes for measurement of water content by nuclear probes. Thermocouple psychrometers were not included at the Fort Carson test section (Figure 6) because past experience indicated that these psychrometers could not be depended on for long-term service (Johnson and McAnear 1974). Figure 7 shows a photograph of the Clinton test site.

18. The test sections were instrumented with 41 to 43 surface heave plates, which are 12-in.-long by 1/2-in.-diam steel reinforcement rods welded to 8- by 8- by 1/2-in. steel plates (Figure 8). These surface plates were placed over the bottom membrane before placement of the sand fill and the top cover.

19. The deep heave plates consisted of 1/2-in. galvanized pipe of the required lengths attached to 2-in.-diam conical stainless tips seated in 3-1/8-in. boreholes (Figure 9). Floor flanges 1-15/16 in. in diameter were placed on the tips rather than conical tips at the Lackland and Fort Carson test sections. After the deep heave plates were seated at the required tip elevation, the boreholes were backfilled with grease to eliminate ponded water in the borehole. Riser pipes 2.5 in. in diameter were placed in the top 2.5 ft of the hole to protect

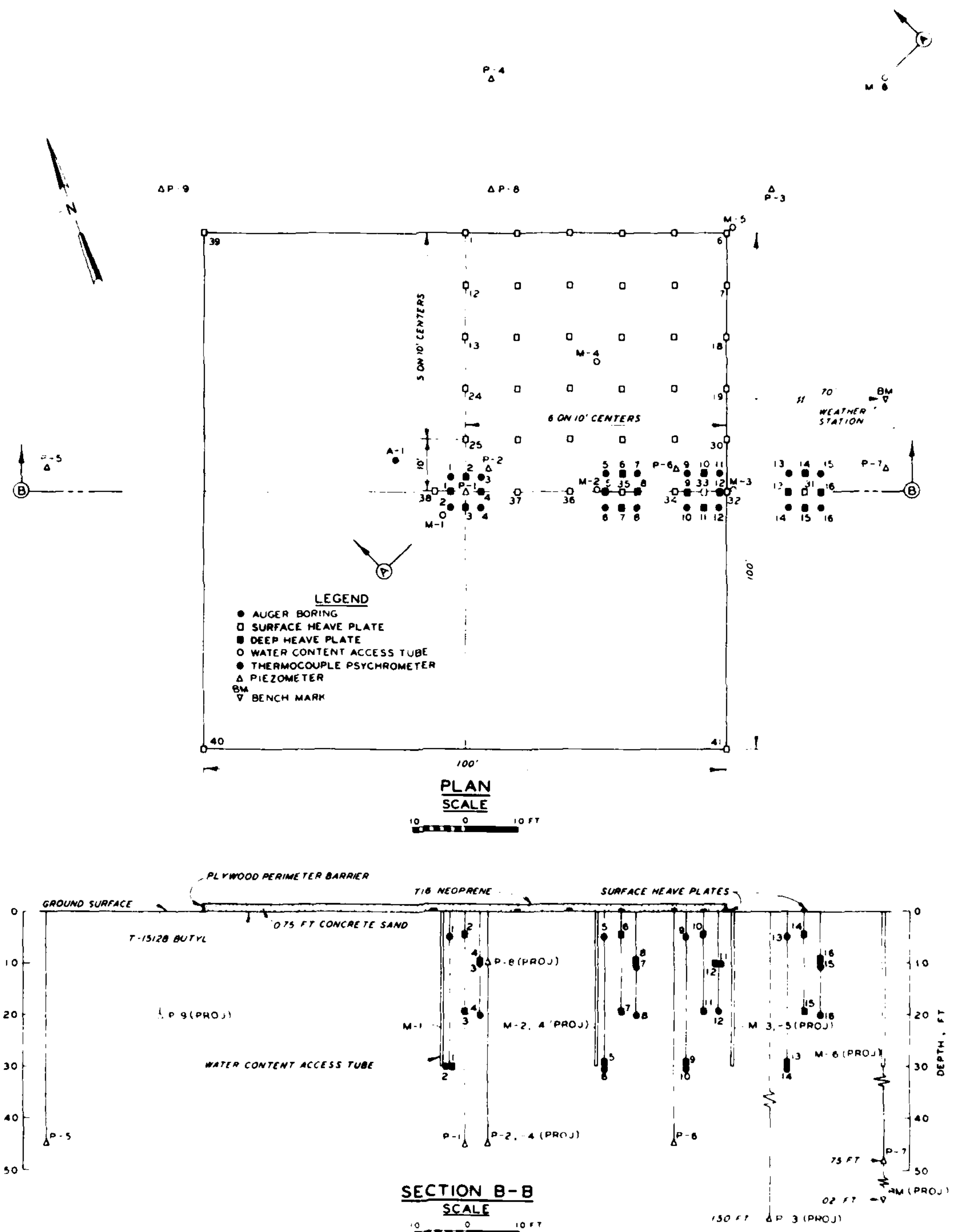


Figure 4. Layout of the Clinton test section

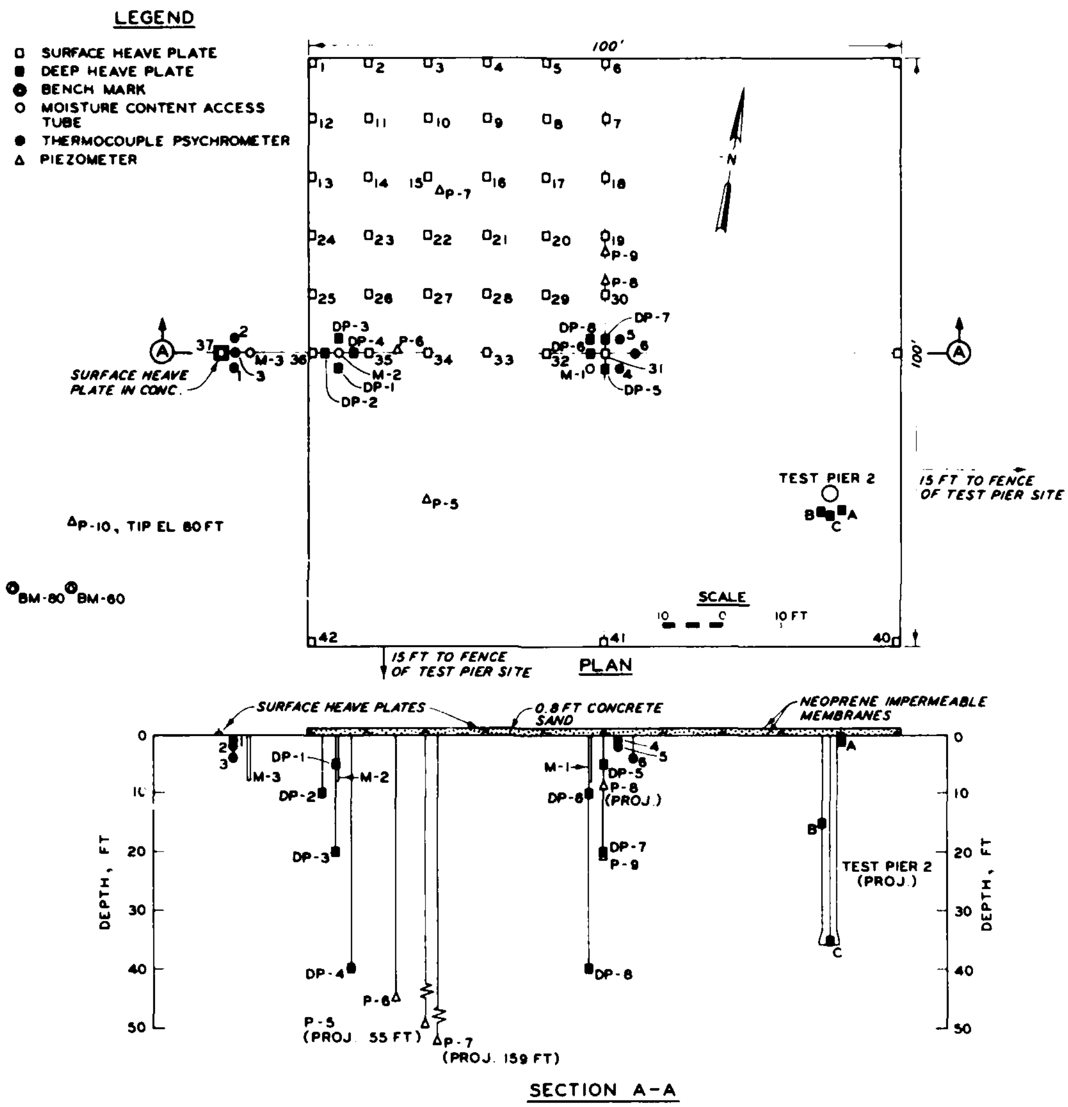


Figure 5. Layout of the Lackland test section

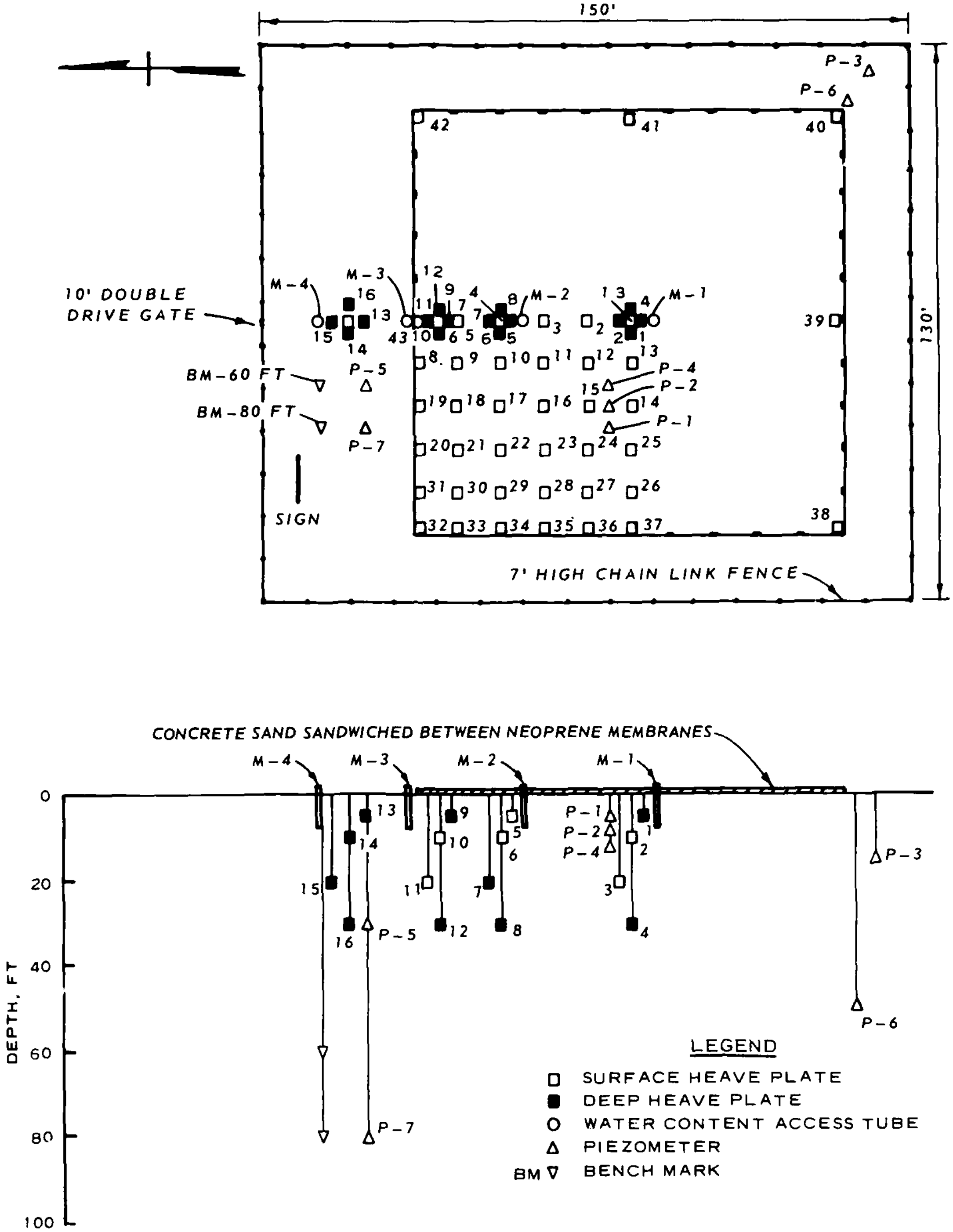


Figure 6. Layout of the Fort Carson test section

Figure 7. View of the Clinton test section

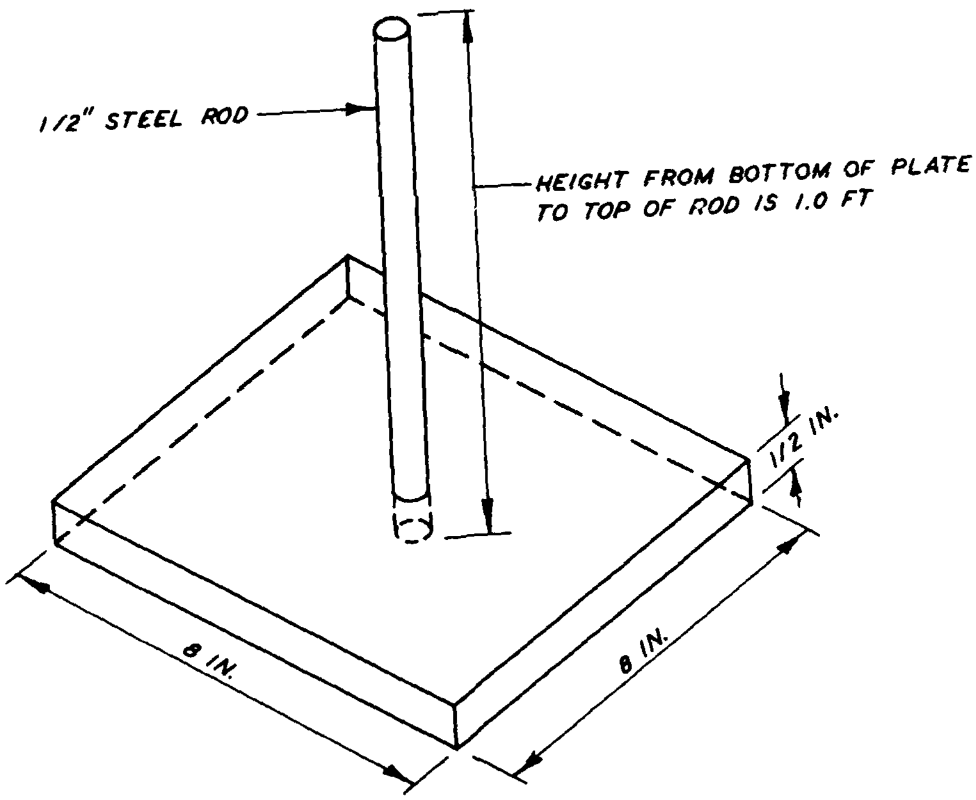


Figure 8. Surface heave plate

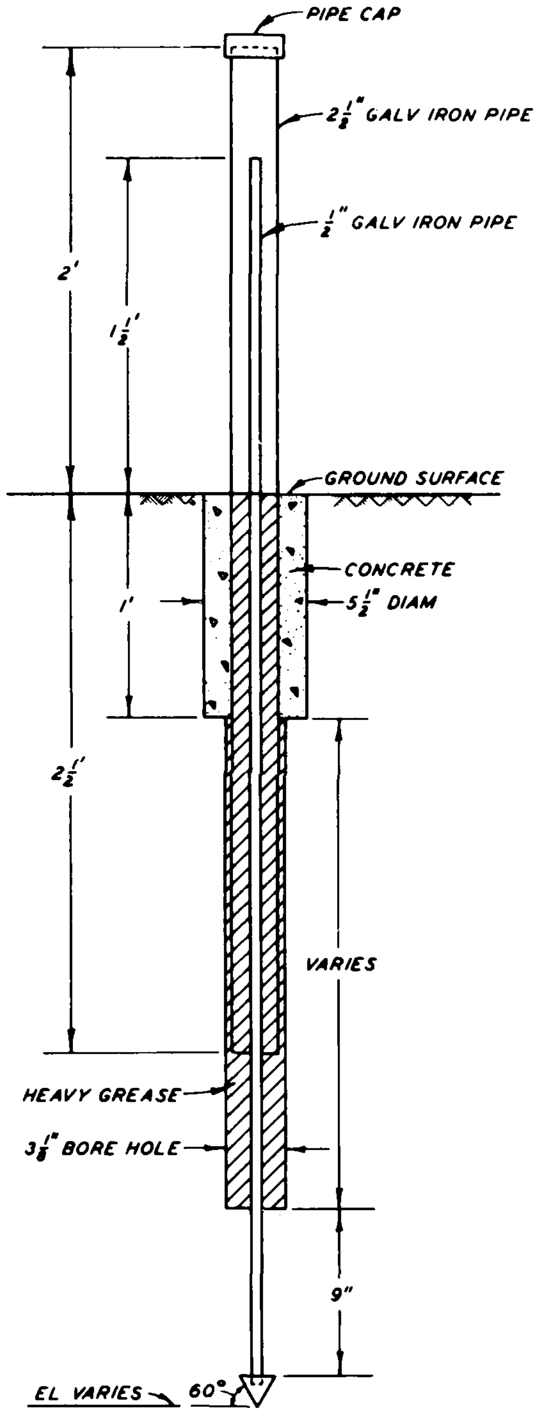


Figure 9. Deep heave plate

the top of the heave plates. The riser pipes were secured in place by a 5.5-in.-diam block of concrete. Further details on instrumentation are provided in Johnson, Sherman, and McAnear (1973) and Johnson (1973b).

Soils

Clinton

20. The predominant soil at the Clinton test site is Yazoo clay, a plastic, stiff marine clay of the Jackson group. The Yazoo clay was deposited in glacial times to a thickness of about 400 ft. In later periods, a lean loessial material ranging in thickness up to 12 ft covered the Yazoo clay.

21. The upper 10 to 15 ft of the Yazoo clay was weathered to a yellowish or greenish-yellow color, frequently stained by limonite and manganese along joints while it was exposed to the environment during its early history. At depths below 10 to 27 ft, the Yazoo clay is unweathered, unjointed, and fairly homogeneous and consists of blue-green to blue-gray calcareous, fossiliferous clay with some pyrite.

22. Classification data of soil from boring samples taken at the center of the test section (Figure 4) are shown in Figure 10. The transition between the lean loess and plastic Yazoo clay is clearly indicated by the abrupt difference in water content at about 6 to 8 ft below the ground surface. The natural water content/plastic limit ratio exceeds 1.2 below 8 ft. Gradation data (Johnson 1978) indicate a relatively coarse soil (20 percent less than 2 μm) at depths less than 8 ft and a relatively fine soil (65 percent less than 2 μm) at depths greater than 8 ft.

Lackland

23. The test section lies directly on an overburden material that varies from 12.5 to 13.5 ft in thickness. About 9 ft of the overburden consists of silty black to gray CH clays containing lime derived from the clay shales of the underlying formation.

24. The primary material underlying the overburden is the Upper Midway group of the Tertiary system. The Upper Midway is a CH

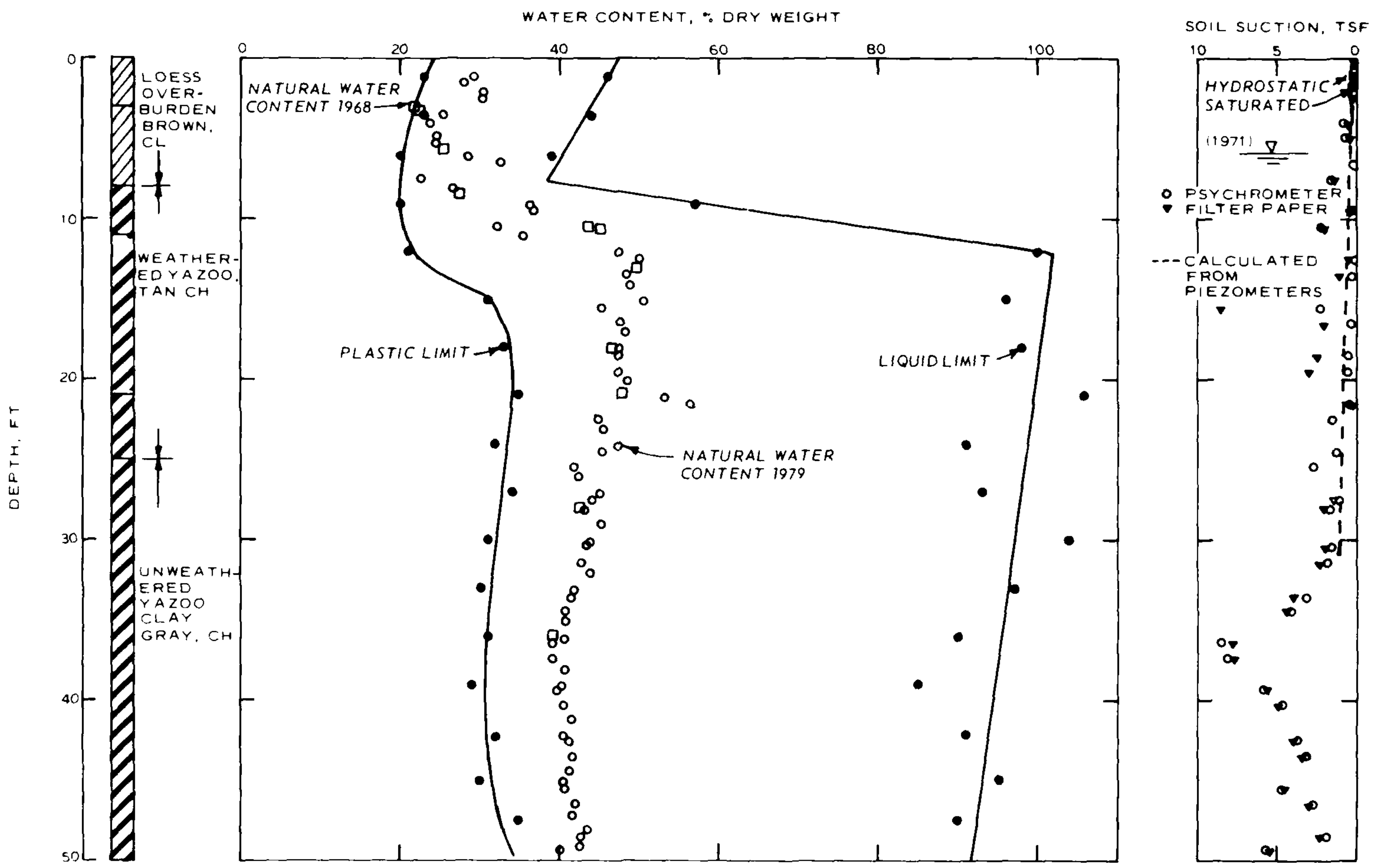


Figure 10. Soil profile of the Clinton test section

montmorillonite clayey shale with the tan, weathered form extending to a depth of about 55 ft; the unweathered bluish form is encountered below this depth. The Upper Midway is highly jointed and slickensided to a depth of about 31 ft below the ground surface.

25. Classification data from boring samples located near the center of the test section (Figure 5) are shown in Figure 11. Boring samples obtained in April 1973 followed a period of rainfall. Natural water contents in the overburden less than 7 ft from the ground surface reflect the wet environment; i.e., the Thornthwaite moisture index at Lackland (Figure 2) is unusually high for 1973. The high natural water contents in the boring samples taken in 1979 reflect the large accumulation of moisture in the soil beneath the test section in June 1973 because of placement of the section.

26. Gradation data (Johnson 1978) indicate that the overburden above 7 ft is coarser than the Upper Midway below the gravel layer; i.e., 40 percent compared to 60 percent less than 2 μm. The clayey gravel between the overburden and Upper Midway contains about 60 percent coarse gravel and 27 percent silt or clay with smaller amounts of fine gravel and sand.

Fort Carson

27. The primary material underlying about 4 ft of brown CH overburden clay is Pierre shale, a sedimentary swelling rock derived from clays and silts. The shale was compressed by the weight of the overlying sediments and glacial ice causing it to be overconsolidated with considerable strength. The shale contains bentonite beds from 1/4 to 6 in. in thickness.

28. The shale, which is badly faulted with frequent slickensided zones, cracks rapidly when exposed to dry air and decomposes to a sticky, gumbo-like mud from repeated wetting and drying. The shale is not chemically cemented.

29. Classification data from boring samples taken from near the center of the test section are shown in Figure 12. Natural water contents are 1.3 times the plastic limit above 8 ft and fall to less than 0.8 times the plastic limit below 15 ft. Gradation data (Johnson 1978) indicate that 40 to 50 percent of the soil particles are less than 2 μm throughout the entire profile.

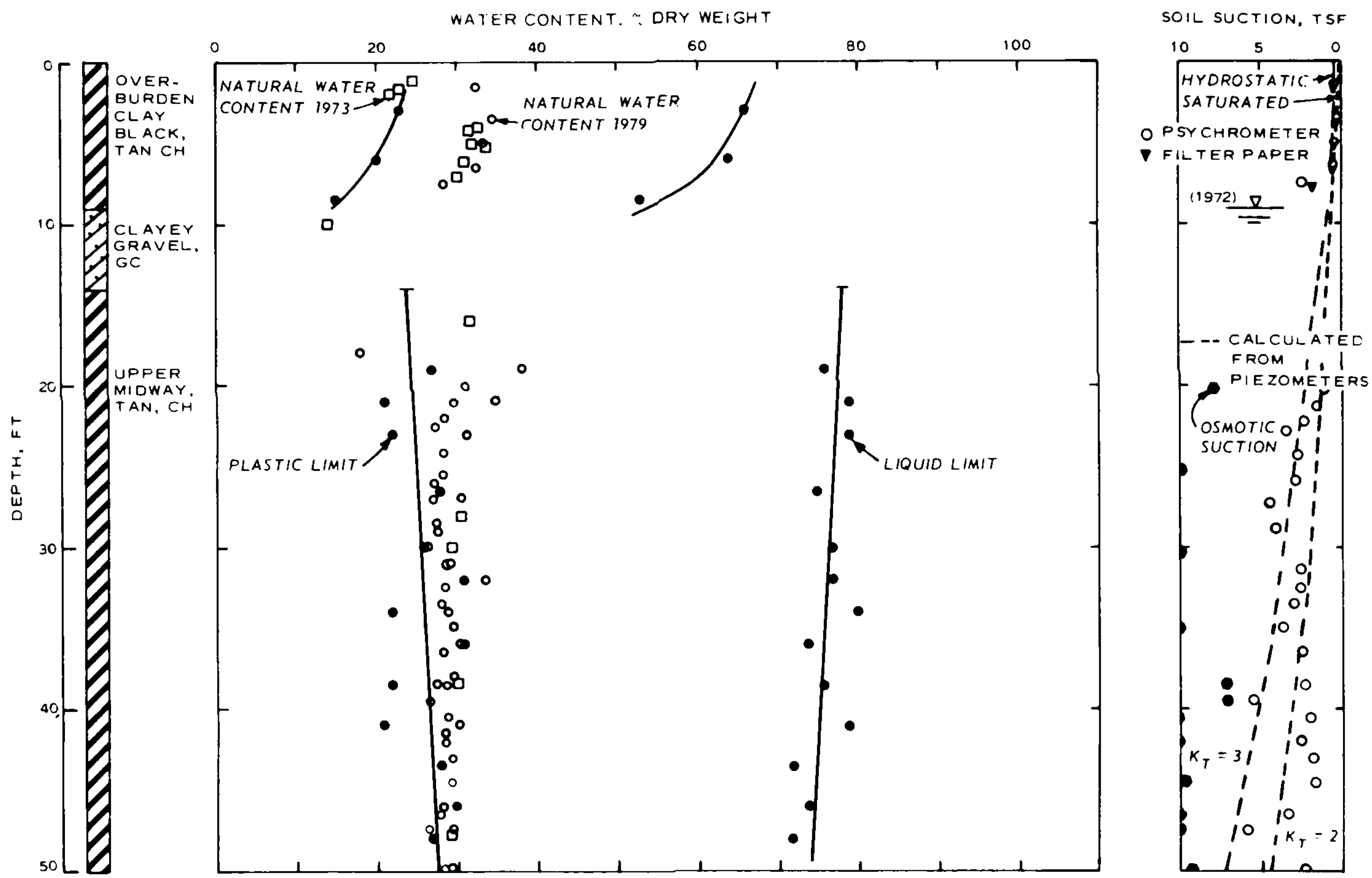


Figure 11. Soil profile of the Lackland test section

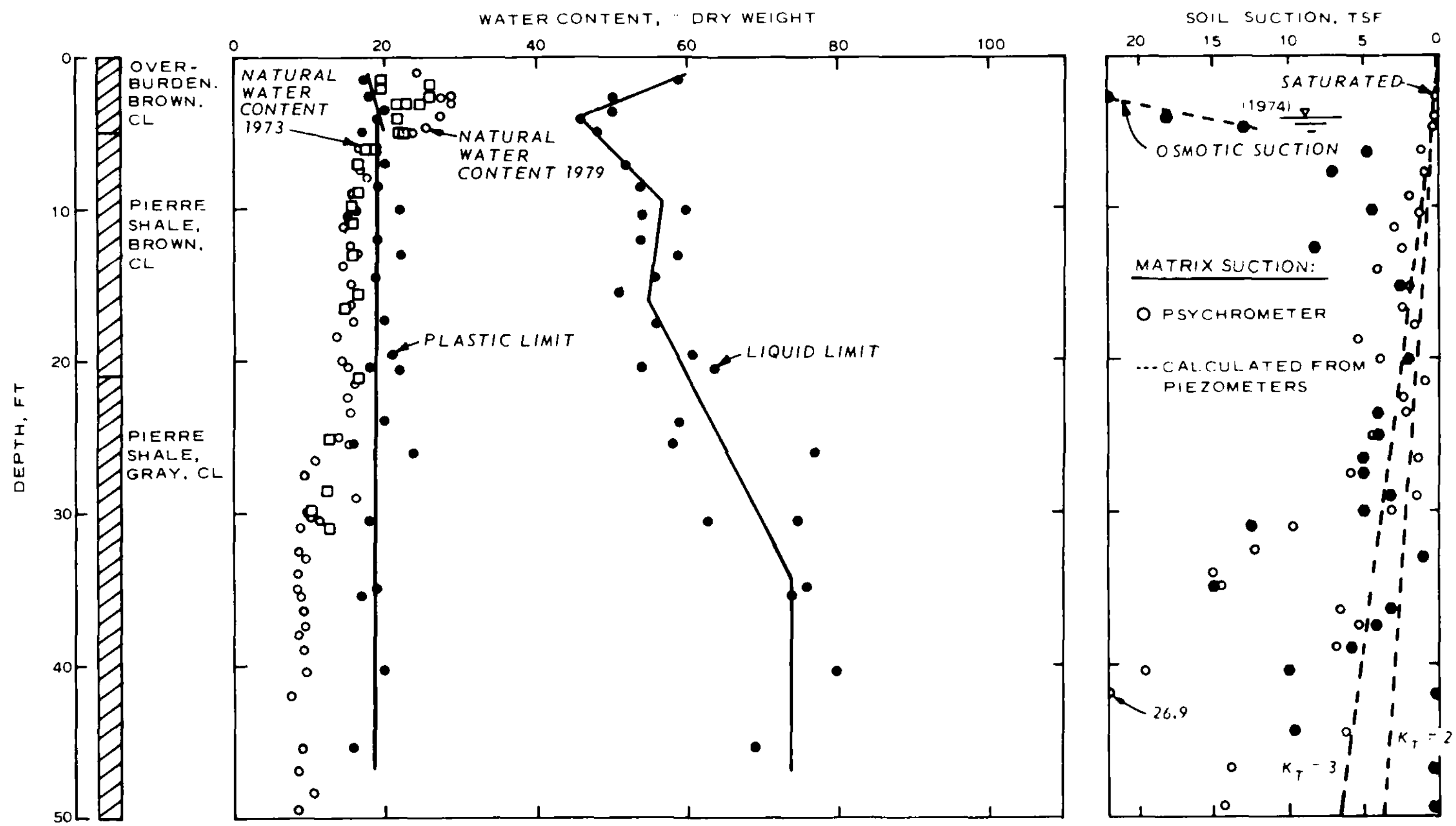


Figure 12. Soil profile of the Fort Carson test section

PART IV: OBSERVATION OF INSTRUMENTS

30. Field observations of water levels in piezometers and elevations of surface and deep heave plates at the Clinton, Lackland, and Fort Carson test sections up to the summer of 1979 are presented below. Data scatter of readings from nuclear probes in aluminum access tubes prevented useful measurements of changes in field water content with time. Soil suctions from the field thermocouple psychrometers are given in Johnson and McAnear (1974).

Clinton Test Section

Piezometers

31. Piezometric readings indicated a perched water table with a water level about 5 ft below ground surface in August 1971 (Figure 13). The pore pressures are consistent with a hydrostatic head in the loess and Yazoo clay down to at least 20 ft below ground surface. The pore pressure head has increased 2 to 3 ft since 1971, indicating wetter soils within 20 ft of the ground surface. Deep piezometers with tips at 45 and 70 ft below ground surface have remained dry since installation in 1968. A deep water table is encountered 124 ft below ground surface.

Vertical heave plates

32. An overall view of the movement of the Clinton test section is provided in Figure 14. Settlement initially observed was attributed to the weight of the sand in the cover coupled with a relatively low rate of heave. Heave has continued to build steadily since 1970 with most heave observed at the center (0.13 ft) and the northwest (NW) corner (0.17 ft) of the section. Grading allows rainwater to run off away from the southeast (SE) corner toward the NW corner and then away from the section. The differential heave between the NW and SE corners could be explained by this grading.

33. Field observations with time of the vertical movement of

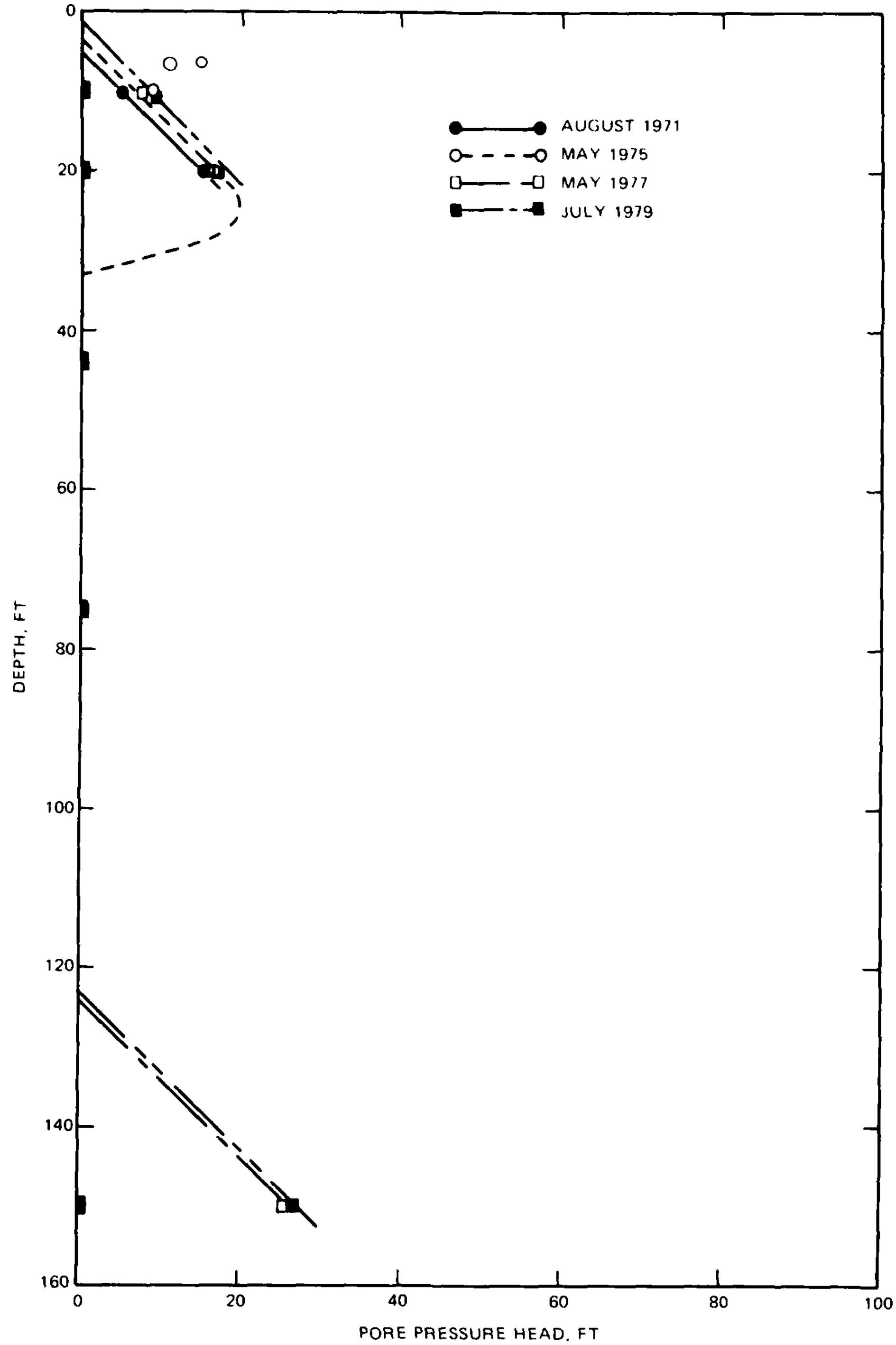


Figure 13. Profile of pore pressure head at the Clinton test site

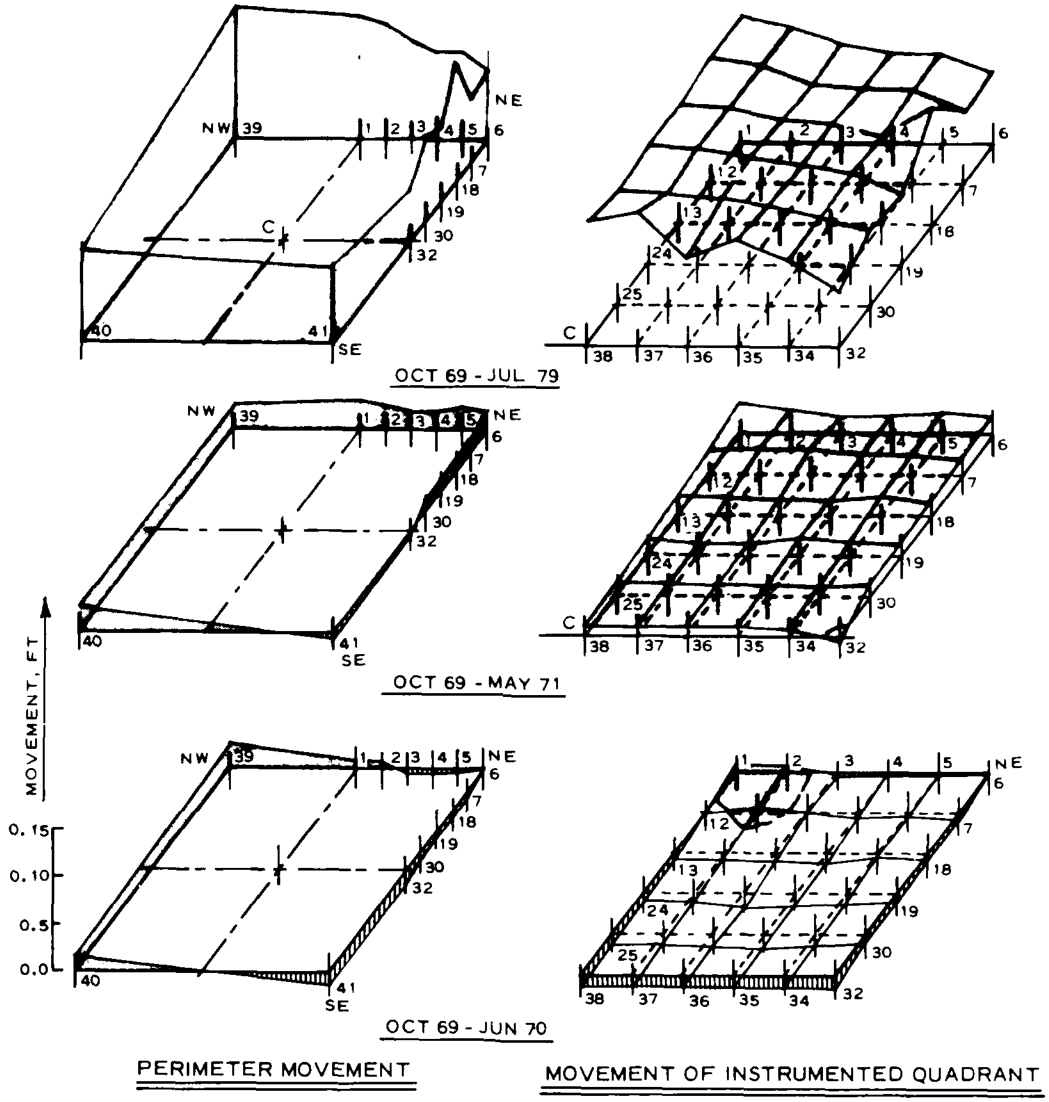


Figure 14. Cumulative vertical movement of the Clinton test section

surface heave plates* at the center (point A), 20 ft inside the edge (point B), 5 ft inside the edge (point C), and 15 ft outside of the test section (point D) are shown in Figure 15. A slight settlement was observed initially up to 500 days following construction of the test section. Heave of about 0.14 ft has subsequently accumulated slowly at

* Upward vertical movement is plotted as positive in all figures.

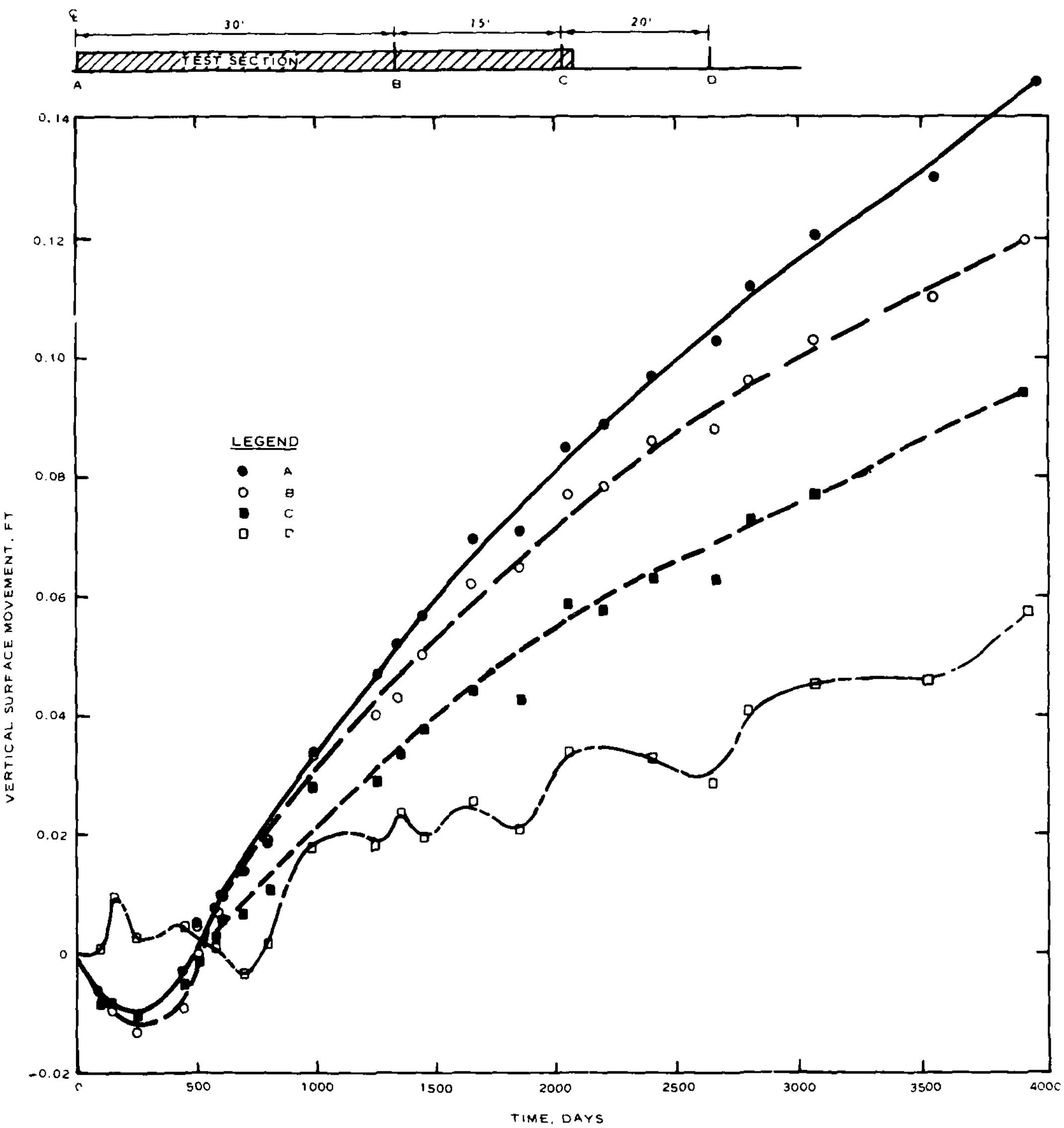


Figure 15. Vertical surface movement with time at the Clinton test section

a decreasing rate up to the most recent observations, 3547 days following construction. Heave was greatest at the center and decreased to about 0.06 ft toward the edge 3900 days (May 1980) following construction of the section. Heave outside of the section at point D was about 26 percent of that at point A. Significant cyclic movement near the edge has not occurred, but slight cyclic movement is evident in Figure 15.

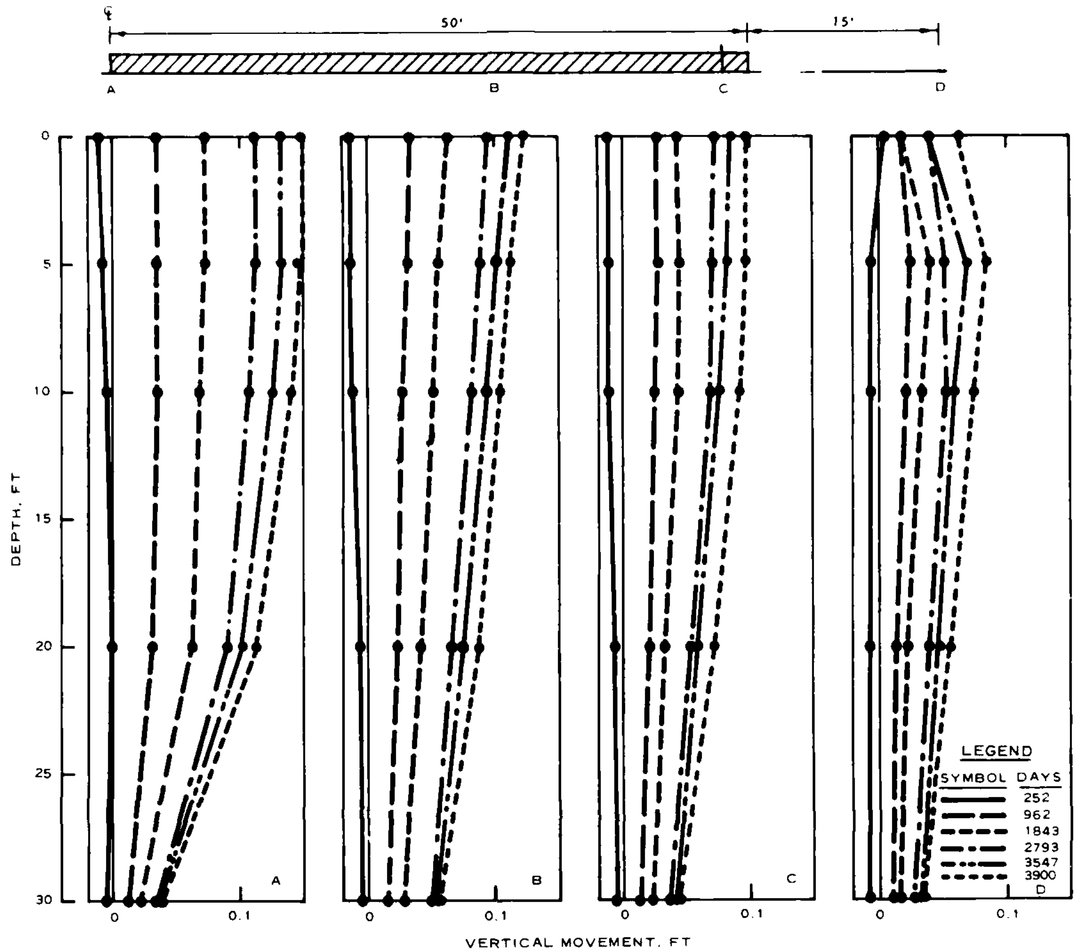


Figure 16. Vertical movement with depth at the Clinton test section

34. Observations of deep heave plates show the distribution of heave with depth (Figure 16). More than 50 percent of the heave originates at depths below 25 ft from the ground surface in the desiccated zone indicated by the piezometric observations. Surface movement at point D down to 5 ft of depth has indicated shrinkage, while some additional swelling is evident below 5 ft. Very little heave has generally occurred within 10 ft of the ground surface, which is consistent with the low swelling capability of the loess overburden. Some deep-seated heave below 30 ft is continuing to accumulate. Although the effect of deeply located heave plugs and piezometers on the observed heave has not been determined, it should be noted that moisture from the perched

water table could be seeping down the perimeters of instruments extending beneath the perched table and thus contributing to the deep-seated heave.

Lackland Test Section

Piezometers

35. Piezometric readings indicated a perched water table with a water level 8 ft below ground surface in September 1972 (Figure 17). The pressure is consistent with a hydrostatic head in the overburden and Upper Midway soils down to 33 ft below ground surface. The pore pressure head decreases between 33 and 45 ft below ground surface. A deep water table consistent with a hydrostatic head was observed below 45 ft in May 1979. At least 7 years was required before the deep piezometers indicated a hydrostatic distribution below the deep water table. The pore pressure head in the perched water table was 5 ft greater in May 1977 and 1979 than in September 1972, but the head has decreased below 33 ft to a very small value at 45 ft.

36. The soil below 33 ft is desiccated or deficient in pore pressure with respect to pressure heads in the perched water table above 33 ft. This pore pressure deficiency may be a potential source of heave.

Vertical heave plates

37. The overall view of movement of the Lackland test section (Figure 18) shows that a substantial portion of the total heave observed by 1979 occurred during the first year. Heave has been distributed fairly uniformly around the perimeter and within the test section. The maximum heave observed is about 0.23 ft.

38. Figure 19, showing the distribution of heave with time, indicates considerable edge effects of cyclic movement outside and near the perimeter of the test section (points A, B, C, and D) caused by variations in seasonal rainfall. Significant shrinkage was observed at points A through D about 500 and 1400 days following construction of the section, periods which correspond to a drought near the end of

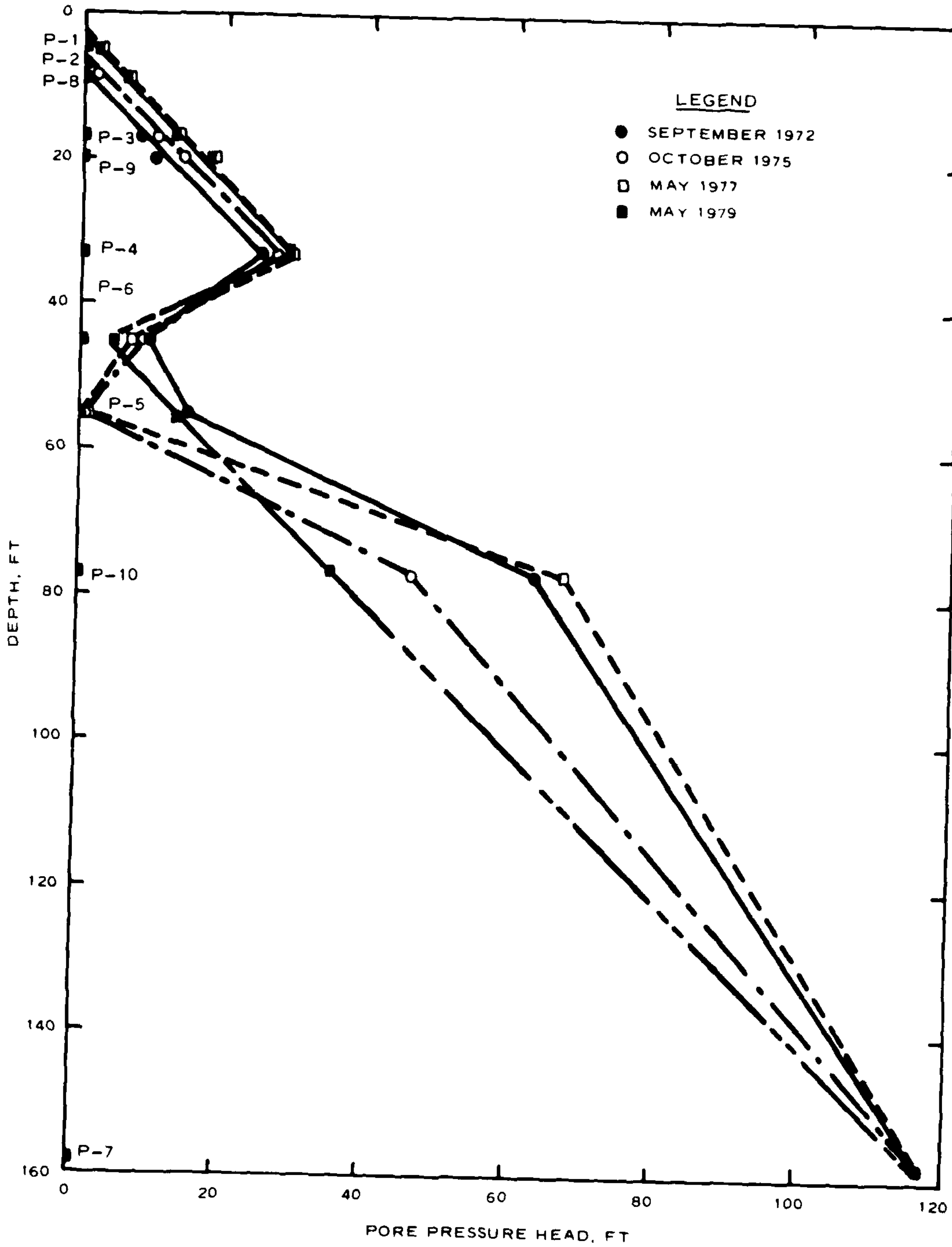


Figure 17. Profile of pore pressure head at the Lackland test site

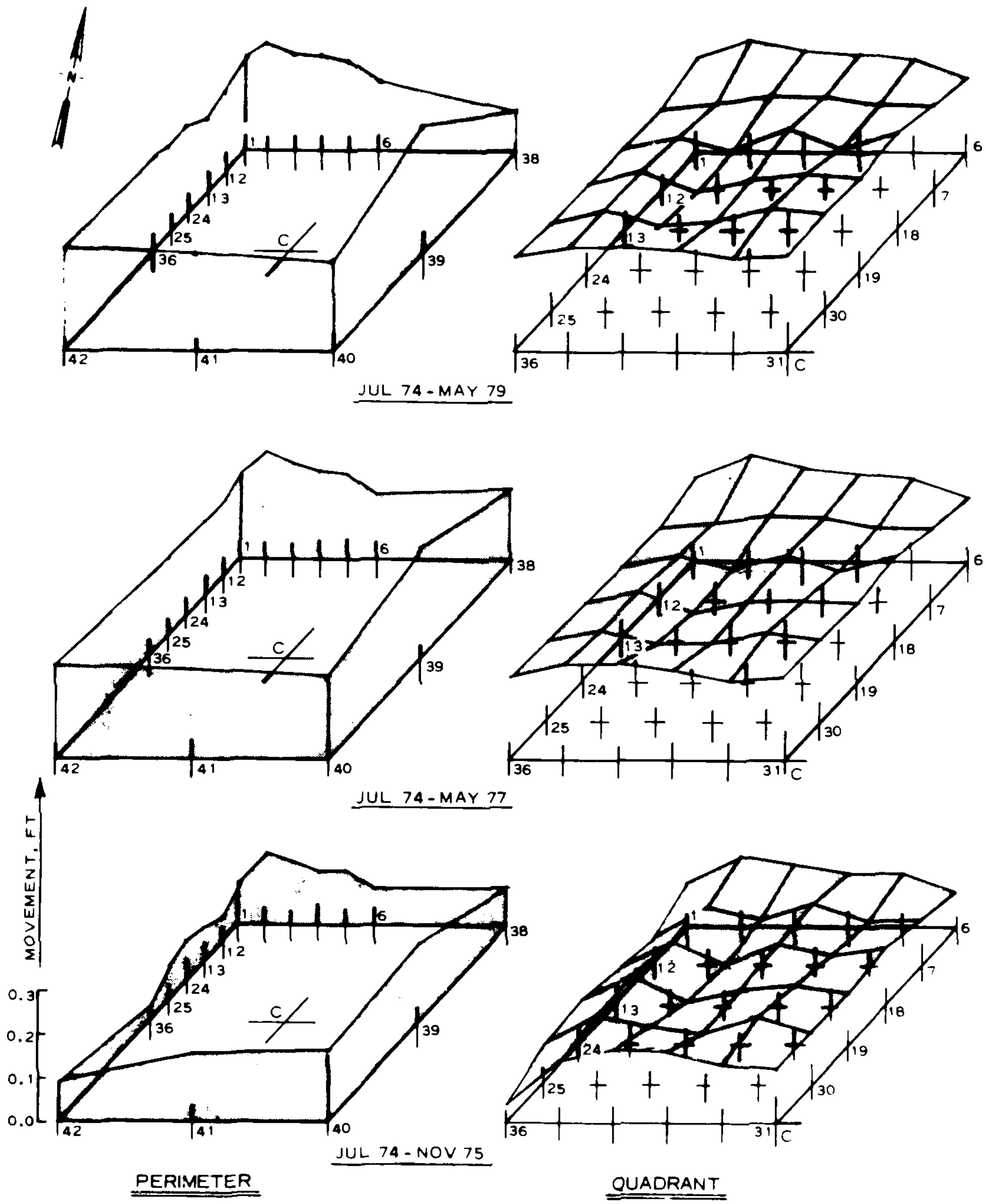


Figure 18. Cumulative vertical movement of the Lackland test section. The vertical scale is reduced to 1/2 of the Clinton test section scale because of the much larger movement observed in a shorter time at the Lackland section

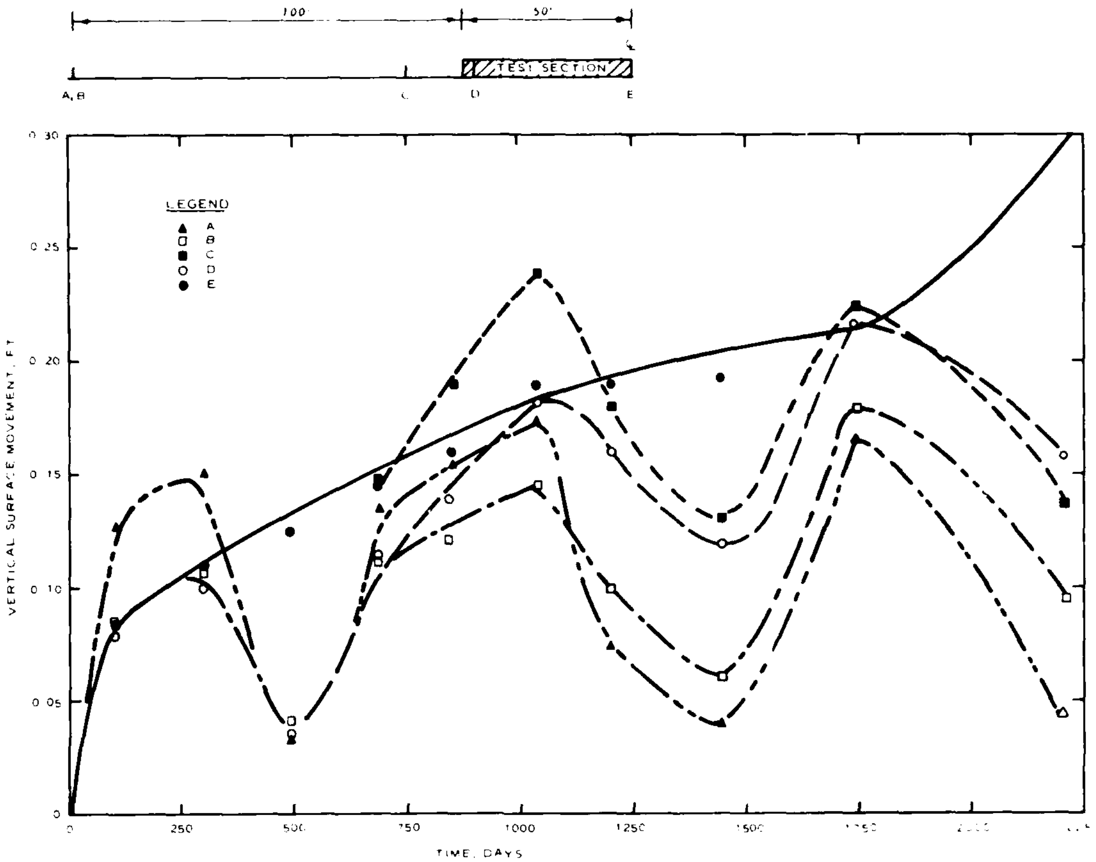


Figure 19. Vertical surface movement with time at the Lackland test section

1975 and the dry years of 1977 and 1978 as illustrated by the moisture indices (Figure 2). Considerable seasonal heave accumulated in 1976 and 1979 (at approximately 1000 and 1800 days), corresponding with a relatively wet environment. This heave exceeded the long-term heave for the same period of time. The boring taken in 1979 had probably contributed to the abnormally large heave at point E after 2200 days. Edge effects were not significant at distances more than 10 ft within the covered area. The rate of accumulation of heave at the center of the section has decreased substantially from the initial high rate observed during the first year of observations.

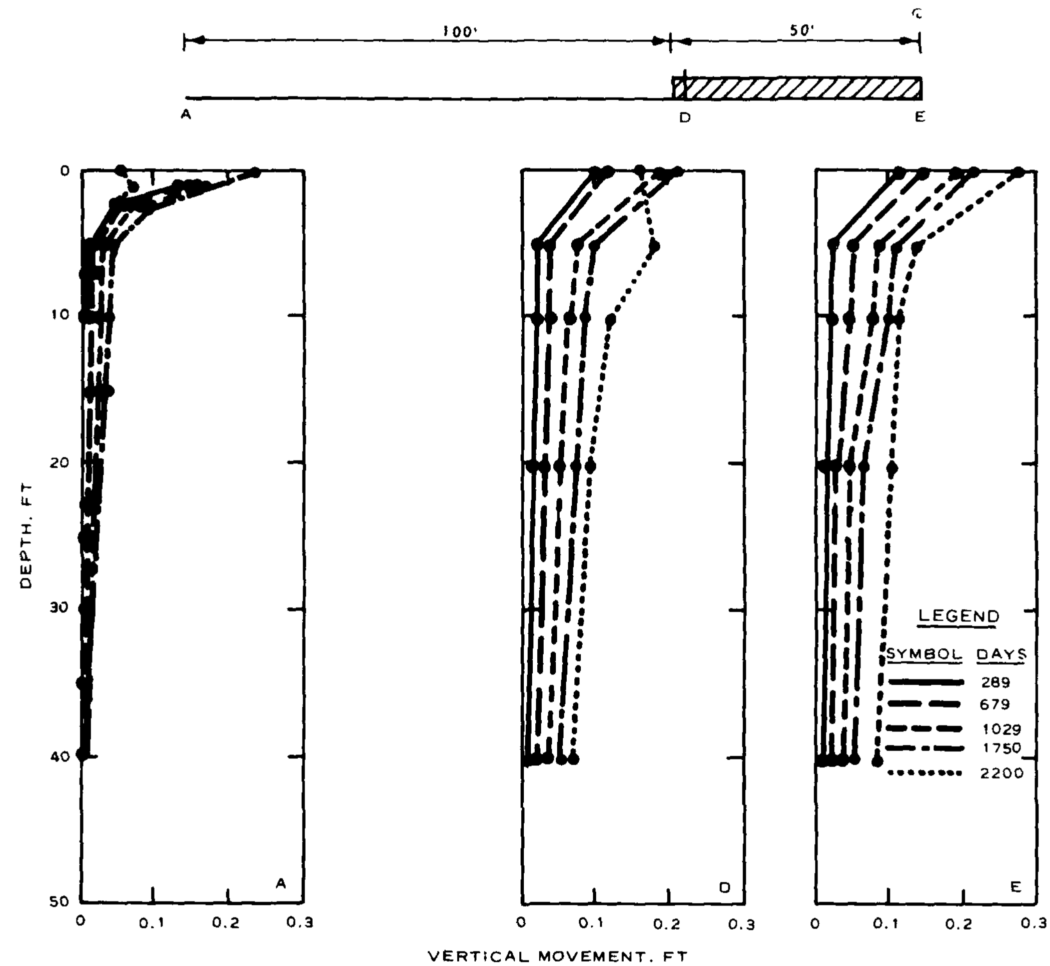


Figure 20. Vertical movement with depth at the Lackland test section

39. The distribution of heave with depth (Figure 20) shows that, at the location 100 ft outside of the test section edge, nearly all of the 0.23 ft of heave at 1750 days following construction originated in the top 5 ft of the overburden soil. Very little heave (about 0.03 ft) occurred between 5 and 40 ft of depth, and negligible heave occurred below 40 ft. About half of the 0.23 ft of total heave beneath the section occurred within the top 5 ft of overburden soil, about 0.06 ft between 5 and 40 ft, and some deep-seated heave of about 0.05 ft occurred below 40 ft of depth. The 1979 sampling operation may have contributed to the heave observed at 2200 days (July 1980). Some moisture from the perched shallow water table may be seeping down the deep heave plates and other instruments into the soil below 40 ft of depth.

Fort Carson Test Section

Piezometers

40. Piezometric readings (Figure 21) indicated a perched water table with a water level about 3 ft below ground surface in October 1974. The pressure is consistent with a hydrostatic head in the Pierre shale down to 30 ft of depth. The pressure head decreased with depth between 30 and 50 ft of depth. The pressure head in the perched shallow water table was about 2 ft greater in May 1977 and 1979 than in October 1974.

41. The deep piezometer with its tip at 80 ft indicated a deep water table below 50 ft. The pressure head at 80 ft is continuing to decrease with time. The zone of soil between 30 and 80 ft appears deficient with respect to the shallow water table above 30 ft. This

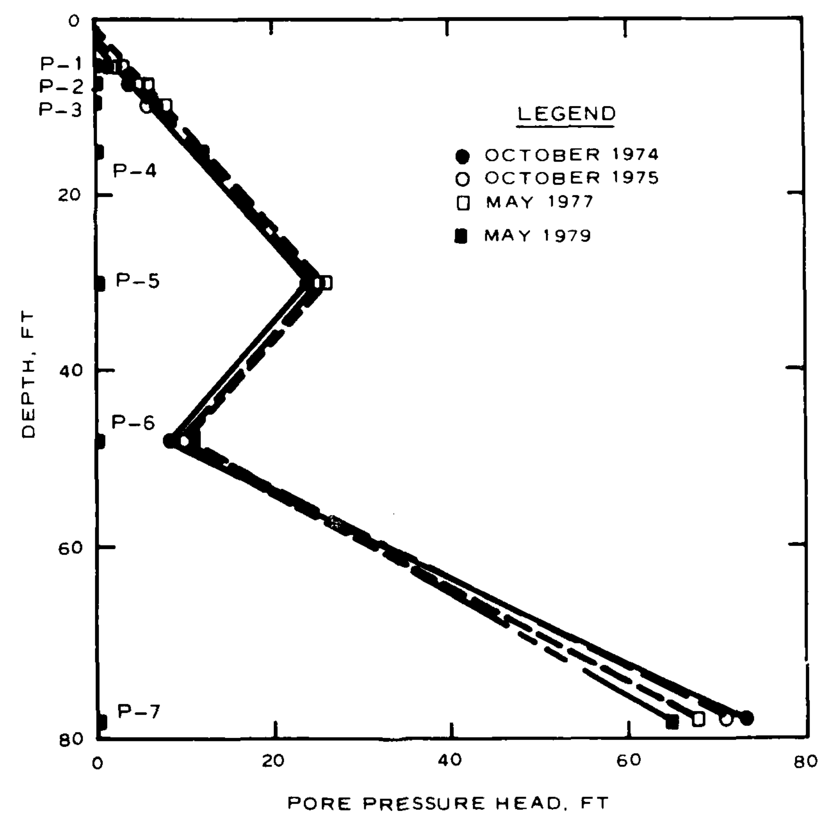


Figure 21. Profile of pore pressure head at the Fort Carson test site

pore pressure deficiency may also be a potential source of heave.

Vertical heave plates

42. The overall view of movement at the Fort Carson test section (Figure 22) shows relatively little heave. Considerable oscillation in

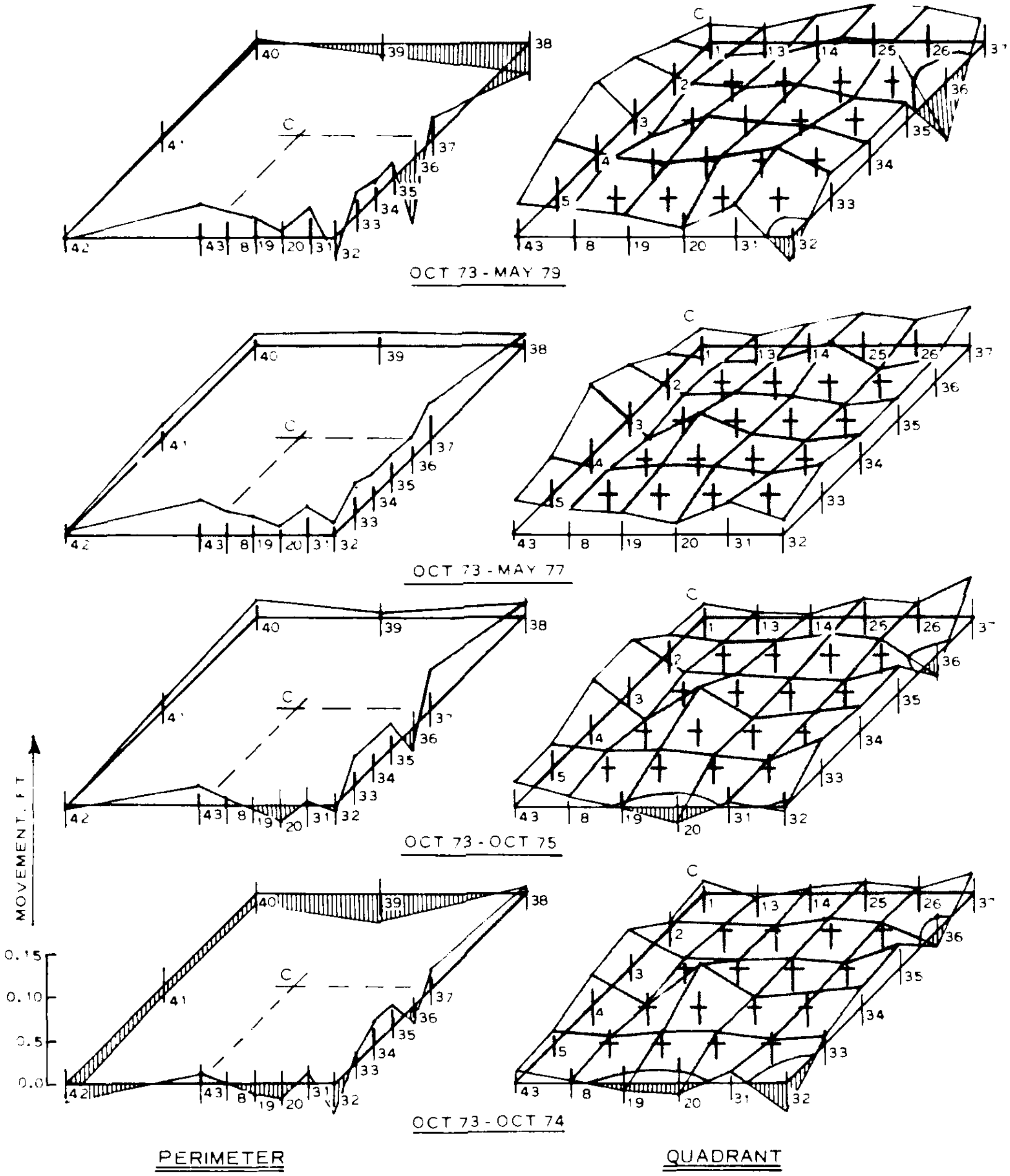


Figure 22. Cumulative vertical movement at the Fort Carson test section

the small seasonal movements at the edge of the test section is apparent. Heave at the center of the section has remained small and less than that observed near the perimeter.

43. Vertical movement with time (Figure 23) indicates the extent of cyclic movement observed outside of the section (point D). Heave at

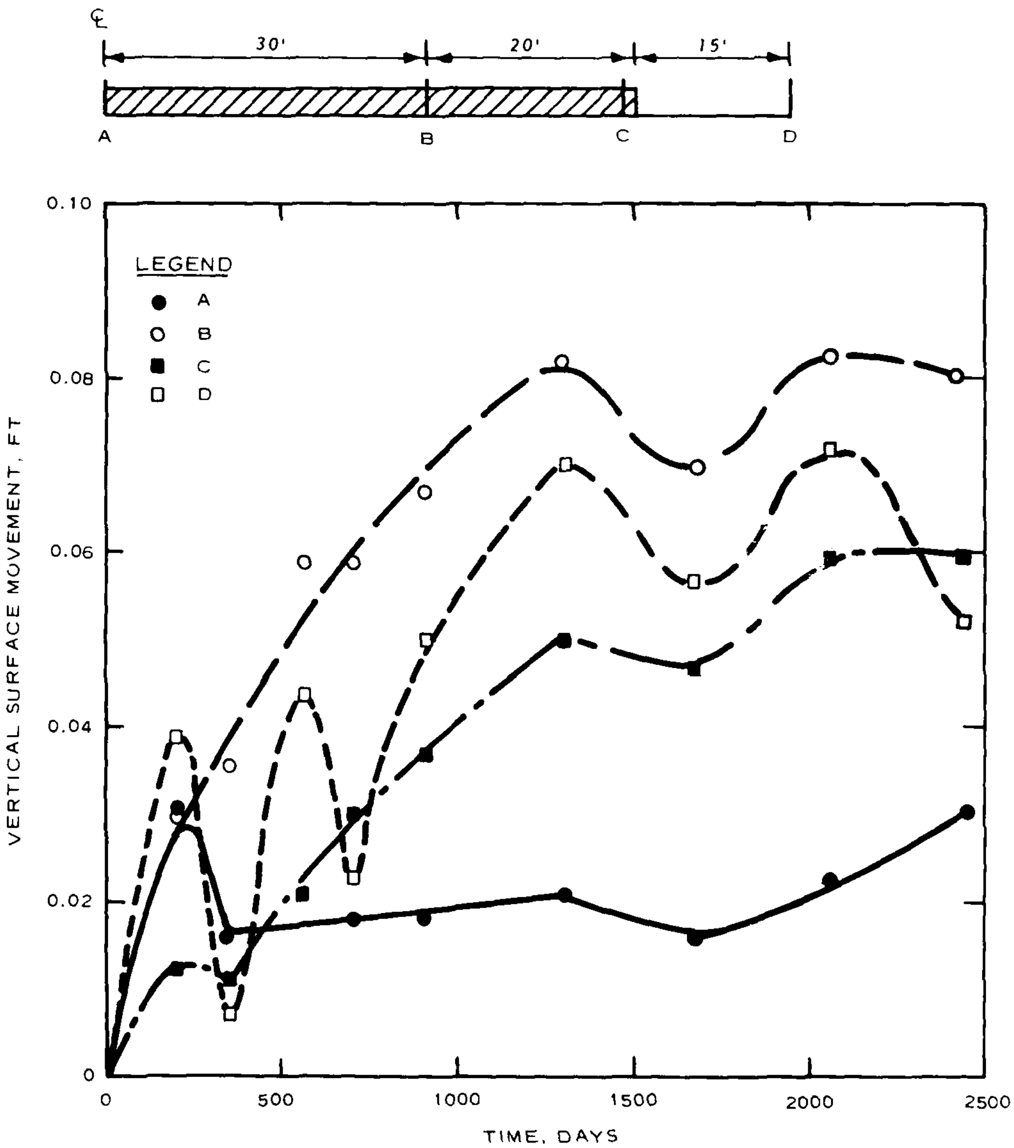


Figure 23. Vertical surface movement with time at the Fort Carson test section

point D is strongly cyclic and influenced by the environment, while heave beneath the covered area is much less influenced by the climate. Edge effects from seasonal moisture are most noticeable at the perimeter of the section and only slightly noticed 10 ft or more within the section. Some shrinkage was observed within the test section about 1700 days following construction, which corresponds to the very dry year observed in 1978 based on the moisture index (Figure 3).

44. Small heaves of about 0.08 ft and less have occurred following construction (Figure 23). Most heave occurred at points B (20 ft inside the edge) and D (outside of the test section), while slightly more than 0.02 ft occurred at the center (point A). Differential heave between points A and B at 2500 days was about 60 percent of the maximum heave at point B.

45. Observations of the vertical movement of the deep heave plates (Figure 24) show that nearly all heave has occurred within 5 ft of the ground surface. Deep-seated heave below 30 ft was negligible 2000 days following construction. The deepest heave plate, located 30 ft below ground surface, is still within the perched water table and does not appear to provide an opportunity for moisture to seep into the pore pressure deficient zone beneath the shallow perched water table. Some slight settlement between 5 and 30 ft of depth was observed at the edge and outside of the test section about 500 days following construction.

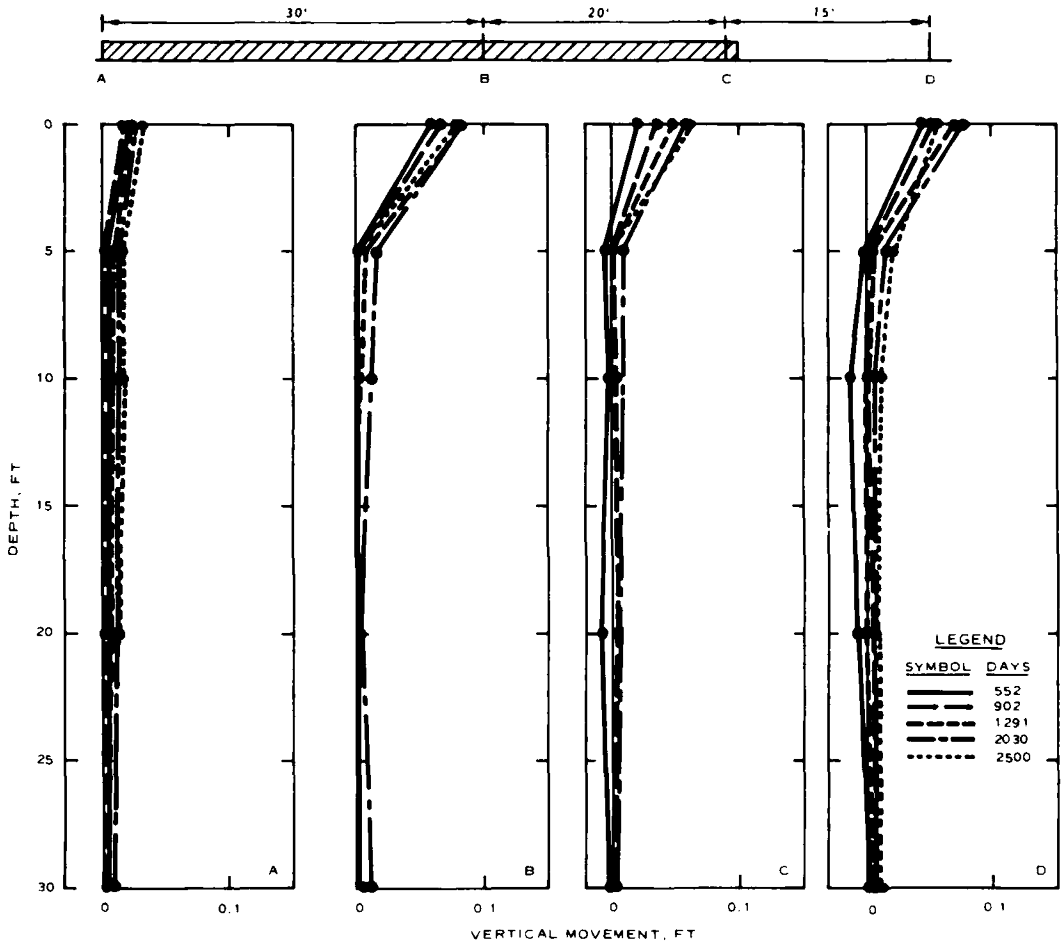


Figure 24. Vertical movement with depth at the Fort Carson test section

PART V: PREDICTION OF POTENTIAL HEAVE

46. Additional heave is expected to accumulate at the field test sections, particularly at Clinton, over many additional years as shown by the trends in the field heaves in Part IV. However, sufficient data are available to clearly show the behavior of soil movement at the field test sections. Predictions of heave in fact have been made previously based on laboratory data determined from testing samples obtained from borings taken near the time of construction of the test sections (Johnson 1978, Johnson and Snethen 1978). The most recent observations of heave discussed in Part IV continue to be consistent with these heave predictions for the Clinton and Lackland test sections. Some revision may be necessary for the Fort Carson test section. Limited new predictions of heave are made in this Part using laboratory test data determined from the most recent boring samples taken in 1979 to confirm or improve characterization of the swelling behavior of the soils at the test sites. These boring samples were located within 3 ft of the center of the test sections.

47. Good predictions of potential heave require reliable estimates of the final or equilibrium pore water pressure or soil suction profile, including effects of well-defined loading conditions, and thorough characterization of the swelling behavior of the soil. The final or equilibrium soil suction profiles beneath the field test sections were evaluated from results of laboratory soil suction tests on boring samples taken during July and August 1979 and from field piezometric data. Soil suctions were evaluated by the thermocouple psychrometer and filter paper methods described in Appendix A. These suction profiles are assumed to be very close to equilibrium.

48. Heave is also influenced by other factors in addition to the equilibrium pore water pressure profile, such as edge effects from droughts and rainfall, groundwater levels, confining pressures, and types of soil. Although the complexity of predicting potential heave may preclude reliable estimates, predictions within 20 to even 50 percent of the actual observed heave are extremely useful for design purposes.

Equilibrium Soil Suction Profiles

49. One of the most difficult problems in applying methods for prediction of heave is to determine a reliable final or equilibrium pore water pressure profile. Many methods assume the final or equilibrium pore water pressure profiles illustrated in Figure 25.

$$\text{Saturated:} \quad u_w = 0 \tag{6}$$

$$\text{Hydrostatic:} \quad u_w = u_{wa} + \gamma_w(X - X_a) \tag{7}$$

where

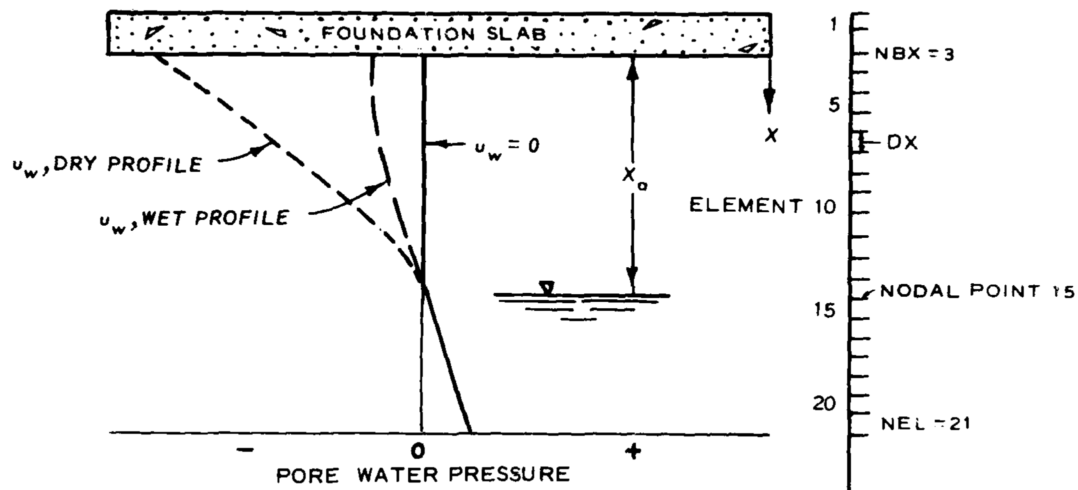
u_w = pore water pressure at depth X, tsf

u_{wa} = pore water pressure at depth of the active zone X_a, tsf

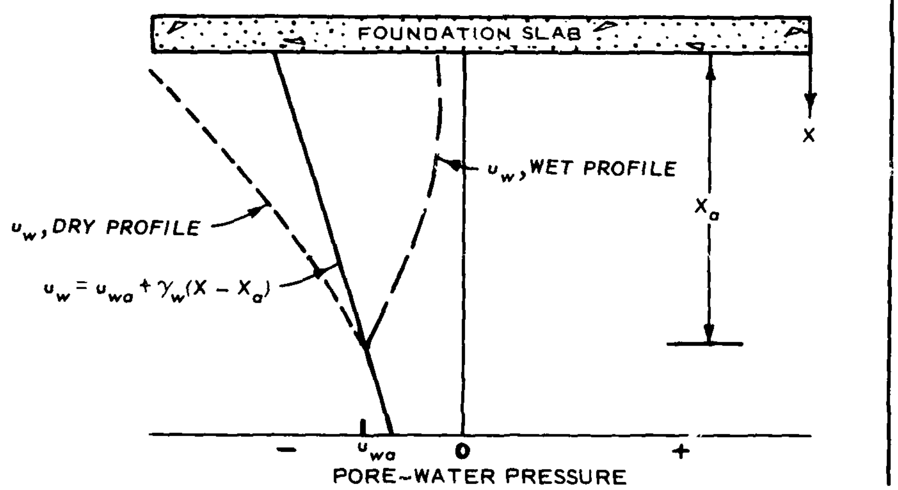
γ_w = unit weight of water (0.0312 ton/ft^3)

Figure 25 shows the difference between example initial dry and wet pore water pressure profiles that may be observed in a soil prior to construction of a foundation. The wet profile is probable following the rainy season, which tends to occur by spring, while the dry profile tends to occur during late summer or early fall (Figures 1-3). The equilibrium "saturated" or "hydrostatic" profiles shown in Figure 25 are assumed to ultimately occur beneath the central portion of the foundation, which is less influenced by seasonal changes in climate.

50. The active zone X_a is defined as the depth below which changes in heave are not observed. The active zone is commonly at about 8 to 10 ft but can extend to deeper depths depending on the depth to groundwater, degree of desiccation, soil structure, and sources of moisture. The saturated profile (Figure 25a) may be more realistic beneath residences and buildings exposed to watering of perimeter vegetation and possible leaking underground water and sewer lines, and particularly where the groundwater level is shallow. A groundwater level less than 20 ft deep in clay soil will influence the suction levels in the soil above the groundwater. A deeper groundwater level may not influence significantly the surface soil suction levels. The negative



a. Shallow groundwater level



b. Deep groundwater level

Figure 25. Assumed equilibrium pore water pressure profiles beneath foundation slabs

hydrostatic profile (Figure 25b) may be more realistic beneath highways and pavements where drainage is good and ponding of surface water is avoided. It is apparent from Figure 25b that extremes in seasonal heave between wet and dry profiles could exceed the long-term heave.

Clinton test section

51. The soil profile (Figure 10) shows the water content and soil suction versus depth relationships. The natural water content data indicate that the soil has become wetter within the top 5 ft of the soil profile since 1968, but soil wetting deeper than 5 ft is not indicated. Observations of field heave (Figure 16) show that very little heave has occurred within 10 ft of the surface. The swelling behavior of the overburden loess is small. Very small or even undetected increases in water content can lead to heave as was actually observed at depths deeper than 10 ft.

52. The equilibrium total soil suction versus depth profile (Figure 10) compares well with the soil suctions calculated from Equation A1 (Appendix A) based on the pore water pressures measured with the field piezometers, except for a few points. The ratio of total horizontal to vertical stress in situ K_T was taken as one. Appendix C provides the total soil suction-water content relationships for the soils beneath the Clinton test section determined by the methods described in Appendix A. The soil suctions above the water table were calculated by assuming saturated (Equation 6) and hydrostatic (Equation 7) profiles and using Equation A1 with observed piezometric pore pressures u_w and α values from Appendix B.

53. The measured total soil suctions in Figure 10 appear to be between those calculated using the hydrostatic and saturated assumptions and are possibly closer to the saturated assumption. However, given the scatter in the suctions and small difference between assumptions, either assumption is possible. The soil suction increases substantially below 30 ft of depth to a maximum of 8 tsf, indicating a desiccated zone of soil. This result is consistent with the dry piezometer tip located at 45 ft of depth. A significant osmotic component of suction τ_s was not detected in the soil beneath the Clinton test section because the

total soil suctions agreed well with the matrix suctions calculated from Equation A1 (Figure 10). Measured total suctions much greater than the calculated suctions suggest a significant osmotic component.

54. Agreement of the small values of suctions at natural water content between the pyschrometer and filter paper methods is good. Agreement between the soil suction-water content relationships from the two methods as shown in Appendix C is not good. However, the lack of agreement may be the result of problems in determining an appropriate calibration curve for the filter paper during these early tests. The calibration curve for the filter paper was found very sensitive to the weighing procedure. Although the calibration curve labeled 2 in Figure A3 (Appendix A) was most applicable and used, it was not considered fully satisfactory.

Lakeland test section

55. The natural water content data shown in the soil profile (Figure 11) indicate some wetting in the overburden clay between 1973 and 1979. Most heave has occurred within the overburden soil as shown in Figure 20. Changes in water content in the Upper Midway clay shale between 1973 and 1979 were not detected, although some deep-seated heave has occurred in the Upper Midway.

56. The measured total soil suction versus depth profile above the perched water table compares well with the suctions calculated from Equation A1 (Appendix A), assuming hydrostatic or saturated moisture profiles (Equations 6 and 7). K_T was taken as one above the water table. Agreement appears to be better for the saturated profile, but again given the uncertainty in the measured suctions and the small difference in the two profiles either profile is possible. The total soil suction data points in Figure 11 were evaluated from the suction-water content curves (Appendix D). A significant osmotic component of soil suction was not detected in the samples of overburden soil, except possibly the sample taken from 7.5 ft (Figure 11) because the matrix suctions calculated from Equation A1 agree well with the measured total soil suctions.

57. Two calculated matrix soil suction profiles using Equation A1, piezometric data, and K_T values of two and three were determined

below the water table (Figure 11). These values of K_T were assumed because the Upper Midway clay shale is heavily overconsolidated (Fort Worth District 1968; Johnson 1978). The total soil suctions at natural water content exceeded the calculated matrix suctions, indicating significant osmotic suctions. A matrix soil suction versus depth profile of the Upper Midway shale was deduced from the measured total suctions by subtracting the estimated osmotic component. Such an osmotic suction is known to exist from previous work (Johnson 1973a). The estimated osmotic suctions (hexagonal points) added to the matrix suctions (open circles) shown in Figure 11 should approximate the total suctions measured by the laboratory tests and shown in Appendix D. Matrix suctions based on total suctions from the filter paper tests are not shown below the perched water table because these are identical with points from the thermocouple psychrometers.

58. The calibration curve labeled 3 in Figure A3 (Appendix A) was most applicable for the weighing and handling procedures used in the filter paper method and was used to reduce the data from the filter paper test. The soil suctions determined by both the psychrometer method and the filter paper method agree well with each other as shown by the comparison of curves and data in Appendix D. However, data from the filter paper method indicated more scatter in results than those from the psychrometer method.

Fort Carson test section

59. The natural water content data shown in the soil profile (Figure 12) indicate that wetting occurred between 1973 and 1979 in the overburden where most of the heave, although not large, has occurred. The total soil suctions measured in the overburden soil above 5 ft were considerable and more than 10 tsf as shown in Appendix E. The matrix suctions calculated from Equation A1, piezometric pore pressure readings, and a coefficient K_T of two were very small (Figure 12). A K_T of two was found representative of this overburden soil (Johnson 1978). The differences between the measured total soil suctions and the calculated matrix suctions are attributed to large osmotic suctions.

60. Chemical analysis of the soluble salts in a 2-g sample of

overburden soil taken from 2 ft of depth suspended in 1 litre of distilled water indicated the following:

Constituent	Concentration mg/l	Concentration milliequivalents/l
SO_4^{--}	57.2	1.191
Ca^{++}	9.1	0.454
Mg^{++}	4.1	0.337
Na^{+}	13.5	0.587

Traces of K^+ and Cl^- ions were also detected. Conversion of these concentrations to the concentration in the pore water indicated about 161 g/l or as much as 4 equivalents/l. Some undissolved salts in the natural soil probably went into solution during the chemical analysis. Nevertheless, these concentrations are consistent with large osmotic suctions in excess of 10 tsf from the tables of Richards (1954) and can completely account for the differences between the measured total soil suctions and the calculated matrix suctions. If the calculated matrix soil suctions are subtracted from the total soil suctions at natural water content shown in Appendix E, then the osmotic suctions are those shown in Figure 12. These osmotic suctions tend to decrease with increase in depth.

61. Two calculated matrix soil suction profiles are shown in Figure 12 for depths below the perched groundwater level, which were obtained using Equation A1, piezometric data, and K_T values of two and three. These values of K_T are reasonable for the heavily overconsolidated Pierre shale (Johnson 1978). Comparison of these calculated matrix suctions with the measured total soil suctions again shows that some osmotic component also may exist below the groundwater level (Appendix E). The total soil suctions at depths below 25 ft are very close to the calculated matrix suctions except for several points (Figure 12 and Appendix E), indicating that the osmotic component is relatively small below 25 ft.

62. Agreement between the soil suction-water content relationships determined by the psychrometer and filter paper methods (Appendix E) is good. The calibration curve for the filter paper

labeled 3 in Figure A3 (Appendix A) was most applicable. The filter paper matrix suction points in Figure 12 are not shown since these are identical with the points for the thermocouple psychrometers.

63. The large magnitudes of osmotic suction deduced from the laboratory chemical analysis and the total soil suctions at natural water content, particularly at the shallow depths, but the small observed heaves show that the osmotic suction has had little influence on field heaves during 7 years of observations. The osmotic suction will normally not influence field heave. Heave from the changes in the osmotic suction may be observed if the concentration of salts in the pore water is significantly altered such as by leaching from moving groundwater. All of the heaves at all three field test sections can easily be explained by the matrix component of suction as shown in the following discussion.

Potential Heave

64. New predictions of potential heave are made for the three test sections for the following cases using the computer program ULTRAT (Johnson 1978):

a. Saturated profile above the water table.

b. Hydrostatic profile above the water table.

c. Saturated profile for a rise in the water table.

d. Hydrostatic profile for a rise in the water table.

The program ULTRAT evaluates the potential heave by the equation

$$\Delta H = N \sum_{i=NBX}^{i=NEL} DELTA(i) = N \cdot DX \sum_{i=NBX}^{i=NEL} \frac{e_f(i) - e_o(i)}{1 + e_o(i)} \qquad (8)$$

where

ΔH = potential (vertical) heave at the bottom of the foundation, ft

N = fraction of volumetric swell that occurs as heave in the vertical direction

NEL = total number of elements

NBX = number of nodal points at the bottom of the foundation

DELTA(i) = potential volumetric swell of soil element i, fraction

DX = increment of depth, ft

$e_f(i)$ = final void ratio of element i

$e_o(i)$ = initial void ratio of element i

The fraction of volumetric swell N that occurs as heave in the vertical direction depends on the soil fabric. Vertical heave of intact soil with few fissures may equal all of the volumetric swell ($N = 1$), while vertical heave of heavily fissured soil may be as low as $N = 1/3$ of the volumetric swell (Richards 1966). ULTRAT assumes $N = 1$, but heave for $N = 1/3$ may be found by dividing the computed heave by three. The initial void ratio may be measured on undisturbed specimens using standard laboratory test procedures described in Engineer Manual 1110-2-1906 (Headquarters, Department of the Army 1970) or during laboratory swell tests. The ΔH is the heave beneath a flexible, unrestrained foundation.

65. The final void ratio e_f depends on the initial field conditions and changes in field conditions caused by construction of the foundation and superstructure. The computer program predicts the final void ratio by either results of consolidometer swell tests or soil suction tests described in Appendix A. Field conditions considered by the program are confinement from soil and foundation loading pressures; equilibrium pore water pressure profiles given by either the saturated or hydrostatic assumptions (Equation 6 or 7, respectively); heterogeneous soil strata; basements; and rectangular, strip, or circular footings.

66. These new predictions of heave provide a check of those made previously (Johnson 1978). The input parameters for the above four cases (Table 1) were determined using data from the recent boring samples obtained in 1979. The compressibility factors defined in Appendix A are given in Appendix B. The soil suction parameters described in Appendix A are given in Appendices C, D, and E. Specific gravities were estimated since these have only a second-order influence on heave.

67. The relative predictions of total potential heave (Table 2) are consistent with the previous predictions for the Clinton and Lackland test sections. The new predictions for the Clinton test section are

Table 1

Input Parameters for Prediction of Heave Using Data from 1979 Boring Samples

Depth ft	Specific Gravity G_s	Initial Water Content w_o percent	Initial Void Ratio e_o	Plasticity Index	Compressibility Factor α	Suction Parameters A	Suction Parameters B	Ratio of Total Horizontal to Vertical Stress In Situ K_T
Clinton Test Site								
0-3	2.67	25.4	0.83	23	0.15	4.000	0.169	1
3-7	2.70	25.4	0.76	21	0.80	4.000	0.169	1
7-10	2.72	34.4	0.98	50	0.90	8.789	0.263	1
Lackland Test Site								
0-2	2.41	25.0	0.78	44	1.00	4.110	0.137	1
2-8	2.41	32.0	0.78	44	1.00	4.110	0.137	1
Fort Carson Test Site								
0-4	2.79	26.0	0.83	31	0.93	7.900	0.333	2
4-9	2.76	16.4	0.54	35	0.75	3.976	0.238	3
9-19	2.74	15.0	0.48	36	1.00	3.976	0.238	3

Table 2

New Heave Predictions

		Test Site		
		Clinton	Lackland	Fort Carson
Observed data beneath center of section:				
Depth to initial water table H , ft		5	8	3
Rise in water table, ft		2	5	1.5
Maximum heave above water table, ft		0.05	0.15	0.08
Maximum extrapolated heave above water table, ft (8000 days)		0.10	0.50	0.20
Total heave at ground surface, ft		0.14	0.23	0.08
Total time, days		3547	1750	2030
Predicted heave above water table, ft:				
Johnson (1978)	Saturated	0.10	0.46	0.17
	Hydrostatic	0.04	0.36	0.15
New	Saturated	0.10	0.44	0.07
	Hydrostatic	0.06	0.28	0.06
Predicted heave including rise in water table, ft:				
Johnson (1978)	Saturated	0.10	0.57	0.19
	Hydrostatic	0.13	0.55	0.18
New	Saturated	0.11	0.49	0.08
	Hydrostatic	0.09	0.45	0.08

approximately the same, while the new predictions for the Lackland test sections are slightly less. The new predictions for the Fort Carson test section are less than half of those originally predicted. Uncertainties in the initial water content and variability of the overburden soil may have been significant in contributing to the original high predictions at the Fort Carson test section. The new predictions for Fort Carson are more consistent with the field observations, particularly heaves recorded at the center of the section. The maximum extrapolated heave at the Fort Carson test section should probably be revised downward from 0.20 ft to about 0.10 ft on the basis of the trends in field data shown in Figure 23.

PART VI: CONCLUSIONS AND RECOMMENDATIONS

68. Predictions of heave are useful for providing guidance on the design and construction of foundations on expansive soils. In the test sections observed, permanent heave accumulates over many years and tends to be erratic, with most heave occurring toward the center of the sections. Seasonal heave can be substantial, even exceeding the long-term heave, for the sections in the semiarid climates. Seasonal heave is not substantial in the wet and humid climate at Clinton. The low-swelling-capacity overburden soil appears to have minimized the seasonal heave. Most of the edge effects due to seasonal heave occur within 10 ft of the edges of the sections, but this is an observable effect that can be felt beneath the entire section.

69. Comparison of measured total soil suctions at natural water content with calculated matrix suctions from piezometric pore water pressures (after discounting any osmotic suctions) shows that the equilibrium pore water pressure is consistent with saturated or hydrostatic pore pressure profiles. For these three sites where shallow water tables exist, the equilibrium pore water pressure profile appears close to the saturated profile. The magnitude of the osmotic component of suction appears to have little effect on heave, even after 7 years of observations. The observed heave is proportional with depth of the water table at the three test sections and can be entirely accounted for by the matrix component of the total suction. Heave predictions from the soil suction data are reasonable and tend to provide upper estimates compared to heave actually observed.

70. The scatter observed in the soil suction data points shows that many tests should be made to increase the reliability of the estimates of potential heave. Tests should be performed at 1- to 2-ft increments of depth. The existence of an osmotic component further reduces the reliability estimates of matrix soil suction from the total soil suction.

71. The field test sections at the Clinton and Lackland test sites should continue to be monitored for several more years since trends in the field heaves indicate potential for considerable additional heave.

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APPENDIX A: EVALUATION OF SOIL SUCTION

Definitions

1. Soil suction is a quantity that can be used to characterize the effect of moisture on volume. It is a measure of the energy or stress that holds the soil water in the pores or a measure of the pulling stress exerted on the pore water. The total soil suction is defined as the sum of the matrix τ_m° and the osmotic τ_s components. The matrix suction is related to the geometrical configuration of the soil and structure, capillary tension in the pore water, and water sorption forces of the clay particles. The matrix suction is pressure-dependent and it is assumed to be related to the pore water pressure u_w by (Croney, Coleman, and Black 1956)

$$\tau_m^\circ = -u_w + \alpha\sigma_m \tag{A1}$$

$$\sigma_m = \frac{1 + 2K_T}{3}\sigma_v \tag{A2}$$

where

α = compressibility factor

σ_m = mean normal confining pressure, tsf

K_T = ratio of total horizontal to vertical stress in situ

σ_v = total vertical pressure, tsf

The compressibility factor is the ratio of the change in specific volume for a corresponding change in water content and is one for saturated soils in which the degree of saturation is one. This factor is usually one for most plastic soils, and α is assumed to be one when calculating the final or equilibrium soil suctions from Equation A1. The compressibility factors measured for the soils beneath the test sections (Appendix B) are generally consistent with this assumption.

2. The osmotic suction τ_s is caused by the concentration of soluble salts in the pore water and is pressure-independent. The

effect of the osmotic suction on swell is not well known, but an osmotic effect may be observed if the concentration of soluble salts in the pore water differs from that of the externally available water. The effect of the osmotic suction on swell behavior is usually assumed small compared to the effect of the matrix suction.

Methods of Evaluation

3. Two methods were used for determining the total soil suction: thermocouple psychrometers and filter paper. The thermocouple psychrometer method is adapted from a technique originally proposed by Spanner (1951), while the filter paper method was adapted by McQueen and Miller (1968) from a technique originally proposed by Gardner (1937). The suction range of thermocouple psychrometers usually is between 1 and 80 tsf, while the range of filter paper varies from less than 0.1 to more than 1000 tsf. Two days is required to reach moisture equilibrium for thermocouple psychrometers, while 7 days is required for filter paper. The thermocouple psychrometer method is simple and can be more accurate than filter paper after the equipment has been calibrated and the operating procedure established. The principal disadvantage is that the suction range is much more limited than that of the filter paper method. The filter paper method is technically less complicated than the thermocouple psychrometer method; however, the weighing procedure required for filter paper is critical and susceptible to large error.

4. Both methods require calibration curves to determine the soil suction from the test results. Calibration is usually performed with salt solutions of various known molality that produce a given relative humidity (Frazer, Taylor, and Grollman 1928). The relative humidities are converted to total soil suction by (Aitchison 1965)

$$\tau^\circ = - \frac{RT}{v} \log e \frac{p}{p_o} \qquad \text{(A3)}$$

where

τ° = total suction free of external pressure except atmospheric pressure, tsf

R = ideal gas constant (86.82 cc-tsf/K-mole)

T = absolute temperature, K

v = volume of a mole of liquid water (18.02 cc/mole)

p/p_o = relative humidity

p = pressure of water vapor, tsf

p_o = pressure of saturated water vapor, tsf

The minus sign in Equation A3 converts the negative total suction to a positive quantity, which is the convention used in this report.

Thermocouple psychrometer method

5. The thermocouple psychrometer measures relative humidity in soil by a technique called Peltier cooling. If a current is caused to flow through a single thermocouple junction in the proper direction, that particular junction will cool, causing water to condense on it when the dew point is reached. Condensation of this water inhibits further cooling of the junction. The voltage developed between the thermocouple and reference junctions is measured by the proper readout equipment. The voltage output is related to the soil suction by a calibration curve.

6. Laboratory measurements to evaluate total suction may be made with the apparatus shown in Figure A1. A thermocouple psychrometer is inserted into a 1-pt-capacity metal container. Then the soil specimen and the assembly are sealed with a No. 13-1/2 rubber stopper. The assembly is inserted into a 1- by 1- by 1.25-ft chest capable of holding six 1-pt containers and insulated with 1.5 in. of foamed polystyrene. Cables from the psychrometers are passed through a 0.5-in.-diam hole centered in the chest cover. Temperature equilibrium is attained within a few hours after placing the lid. Equilibrium of the relative humidity in the air measured by the psychrometer and the relative humidity in the soil specimen is usually obtained within 24 to 48 hours.

7. The calibration curves of 12 commercial (Wescor) psychrometers

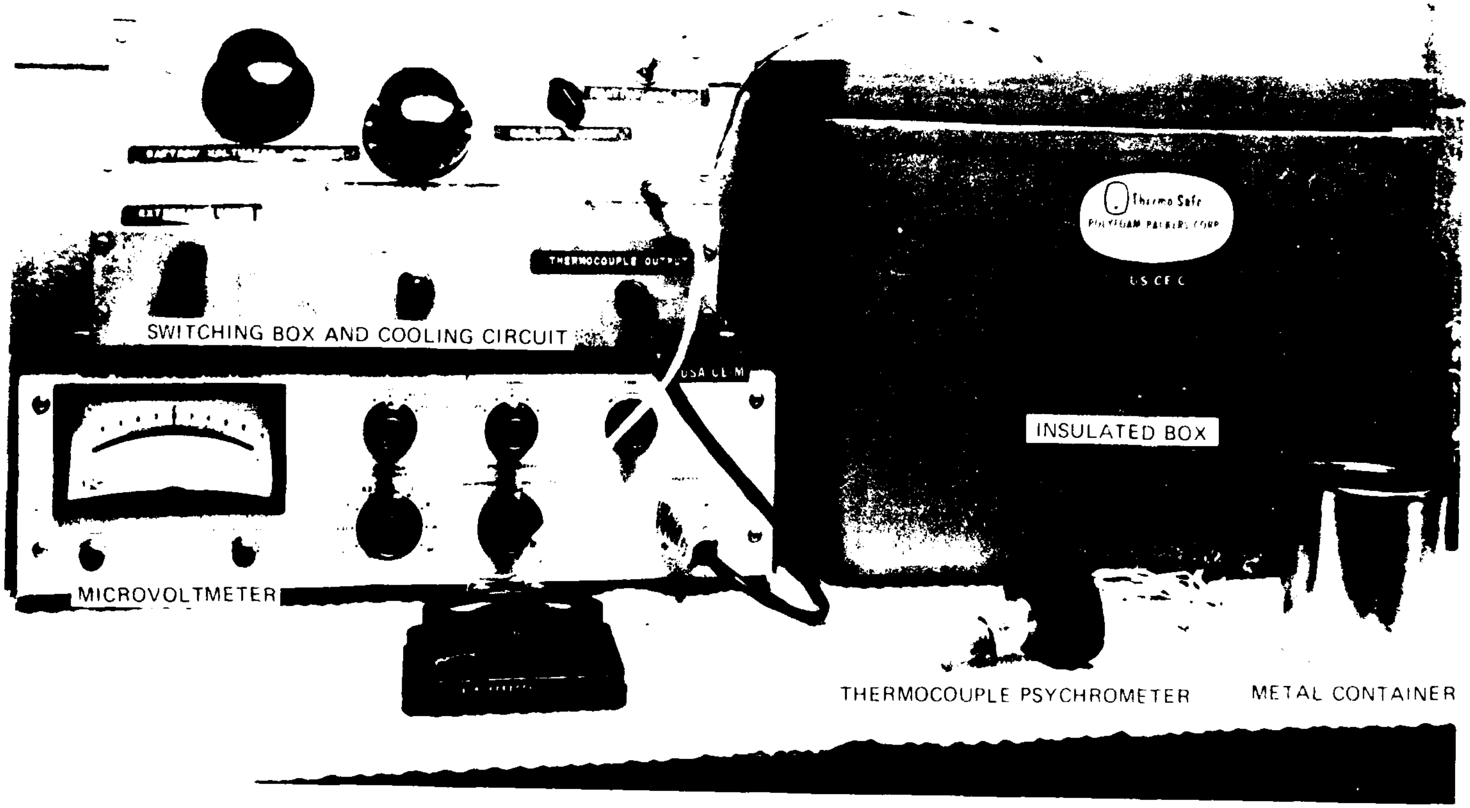


Figure A1. Thermocouple psychrometer monitoring apparatus

acquired for the subject study were within 5 percent and could be expressed by

$$\tau° = 2.65E_{25} - 1.6 \qquad \text{(A4)}$$

where

$\tau°$ = total suction, tsf

E_{25} = microvolts at 25°C

The monitoring system (Figure A1) includes a cooling circuit with the capability of immediate switching to the voltage readout circuit on termination of the current (Figure A2). The microvoltmeter should have a maximum range of at least 30 μv and allow readings to within 0.1 μv. The 12-position rotary selector switch (item 2 in Figure A2) allows up to 12 simultaneous psychrometer connections. The 0- to 25-mA milliammeter (item 3), two 1.5-v dry cell batteries (item 4), and the variable

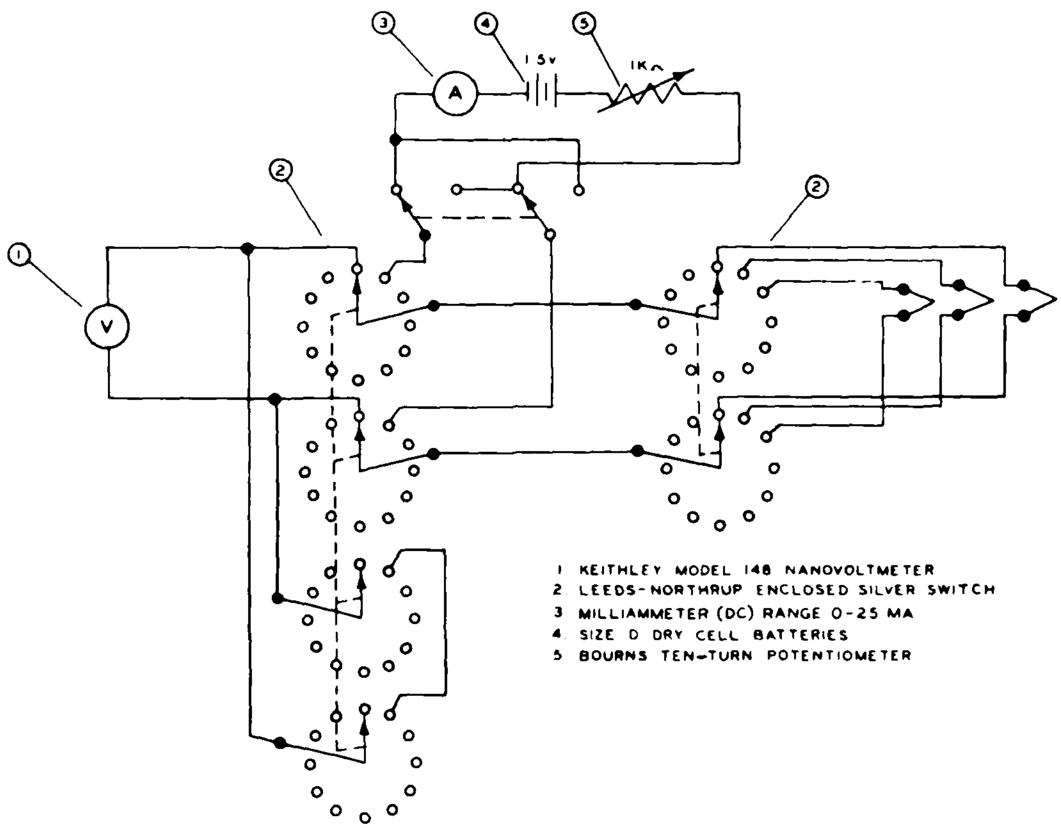


Figure A2. Electrical circuit for the thermocouple psychrometer

potentiometer (item 5) form the cooling circuit. The optimum cooling current is about 8 mA applied for 15 seconds.

8. The readings can be taken at room temperature, preferably from 20 to 25°C, and corrected to E_{25} by

$$E_{25} = \frac{E_t}{0.325 + 0.027t} \quad \text{(A5)}$$

where E_t is the microvolt output at t°C . Placement of the apparatus in a constant temperature room will increase accuracy of the readings.

Filter paper method

9. This method involves enclosing filter paper with a soil specimen in an airtight container until complete moisture equilibrium is reached. The water content in percent of the dry weight is subsequently determined and the soil suction found from a calibration curve. The 5.5-cm-diam filter paper disc is pretreated with 3 percent pentachlorophenol in ethanol (to inhibit deterioration) and allowed to air-dry. Care is required to keep the filter paper from becoming contaminated with soil from the specimen, free water, or other contaminant.

10. Seven days is required to reach moisture equilibrium in the airtight container. At the end of 7 days, the filter paper is transferred to a 2-in.-diam covered tare and weighed immediately on a gravimetric scale accurate to 0.001 g. The number of filter papers and tares weighed at one time should be kept small (i.e., 9 or less) to minimize error due to water evaporating from the filter paper. The tare is opened and placed in an oven for at least 4 hours or overnight at a temperature of 110 ± 5°C. The ovendry weight of the filter paper is then determined, and the water content as a percent of the dry weight is compared with a calibration curve to determine the soil suction.

11. The ovendry water content of the filter paper is dependent on the time lapse following removal from the drying oven before weighing. The calibration curves shown in Figure A3 were determined for various elapsed times following removal from the oven. The calibrations are given for Fisherbrand filter paper, Catalog Number 9-790A, enclosed with salt solutions of various molality for 7 days. The curves are

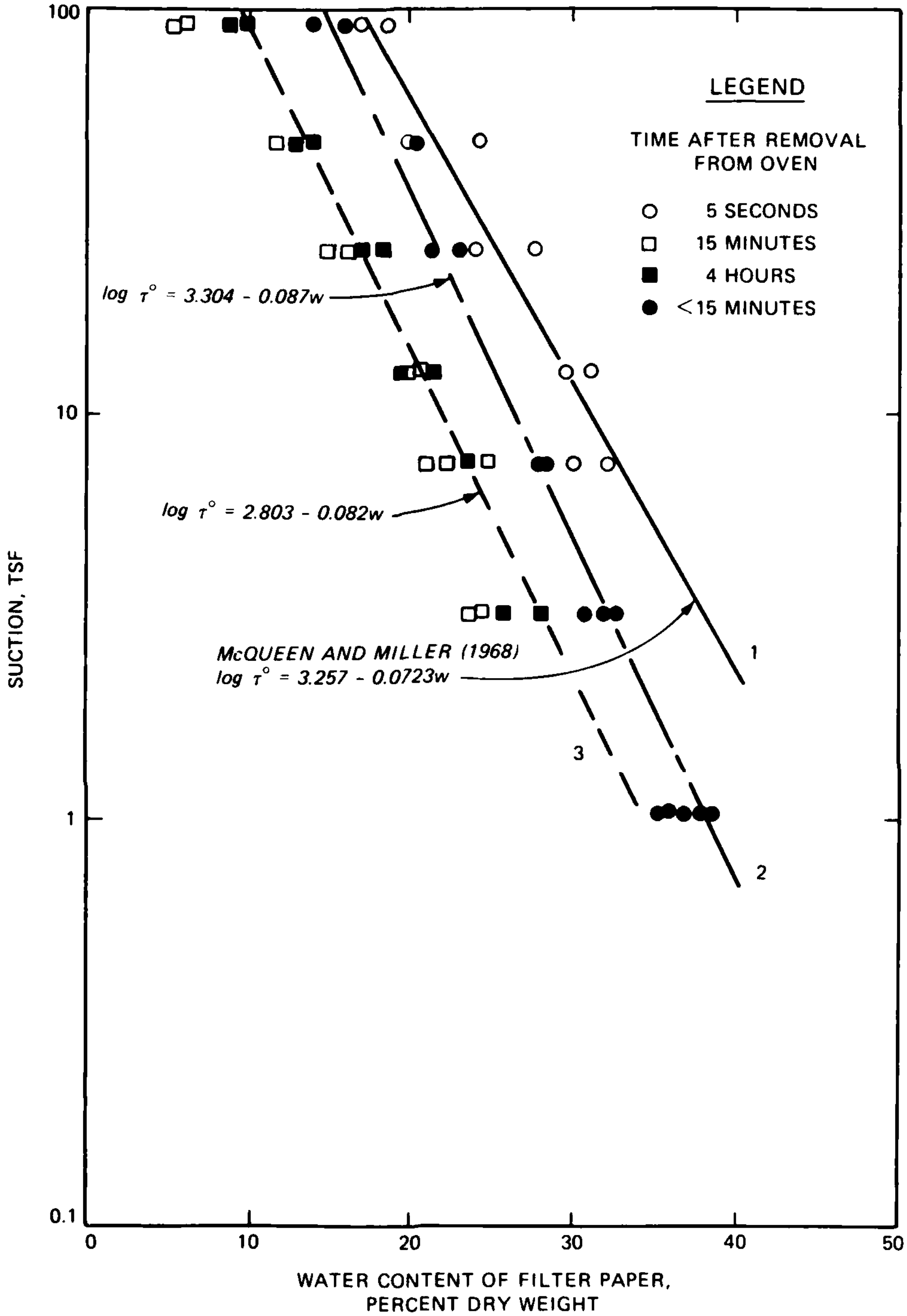


Figure A3. Calibration of filter paper

steep and not conducive to accurate evaluation of suction. The curve for a time lapse of 5 seconds reproduces the calibration determined by McQueen and Miller (1968) who also weighed the filter paper 5 seconds following removal from the oven. Time lapses of 15 minutes and 4 hours lead to a similar calibration curve of significantly smaller water contents than the 5-second curve for identical suctions. The third calibration curve was determined by removing 12 specimens from the oven, waiting 30 seconds for them to cool, then weighing the specimens (tares containing the specimens) as soon as possible.

12. The 4-hour calibration curve is recommended if the suctions of large numbers of specimens are to be evaluated. The upper suction range of the 4-hour calibration curve is limited to about 1000 tsf, which is much more than adequate for practical applications and still higher than that available with the psychrometer. The 5-second curve is not practical unless the scale is located near the drying oven. Changes in filter paper weights are normally small (e.g., <0.1 g) and require accurate scale calibration and adherance to a single standardized routine.

Soil Suction-Water Content Relationship

13. The total soil suction-water content relationship of a particular soil is evaluated from multiple 1-in. pieces of the undisturbed sample. The pore water is evaporated at room temperature for various periods of time up to about 48 hours from several undisturbed specimens; various amounts of distilled water are also added to several other undisturbed specimens of each sample to obtain a multipoint water content distribution. Each specimen is inserted into a 1-pt metal container with a thermocouple psychrometer or with filter paper for evaluation of the total soil suction as previously described. The dry density and void ratio of each undisturbed specimen are evaluated by the water displacement method described in Engineer Manual 1110-2-1906 (Headquarters, Department of the Army 1970).

Matrix suction

14. The multipoint total soil suction-water content relationship

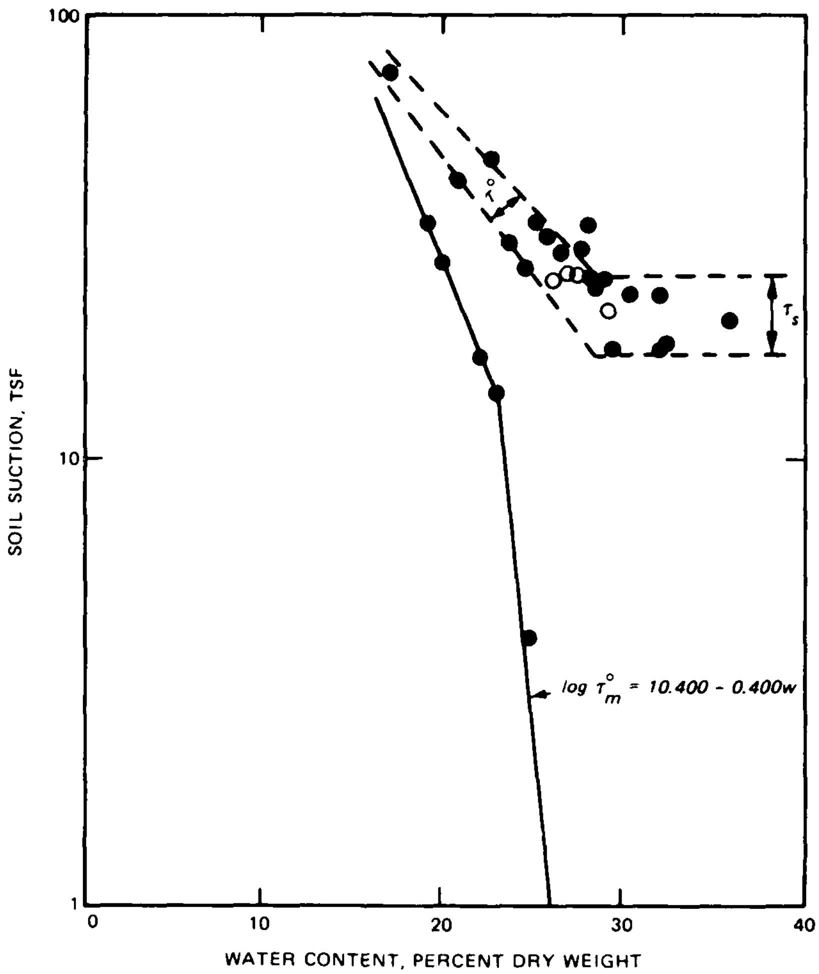


Figure A4. Soil suction-water content relationship for Fort Carson overburden at 1.0 to 3.0 ft of depth

is plotted as shown in Figure A4 for each undisturbed sample. An osmotic suction τ_s is sometimes indicated by a horizontally inclined slope at high water contents, and the magnitude may be estimated by noting the total soil suction at high water contents. Large osmotic suctions appreciably flatten the slope as shown in the figure. The matrix suction-water content relationship can be approximated by subtracting the osmotic suction from the total soil suctions and expressing the results as

$$\log \tau^{\circ}_{m} = A - Bw \qquad \text{(A6)}$$

where

τ_m^o = matrix suction without surcharge pressure, tsf

A = ordinate intercept of the soil suction-water content curve, tsf

B = slope of the soil suction-water content curve

w = water content, percent dry weight

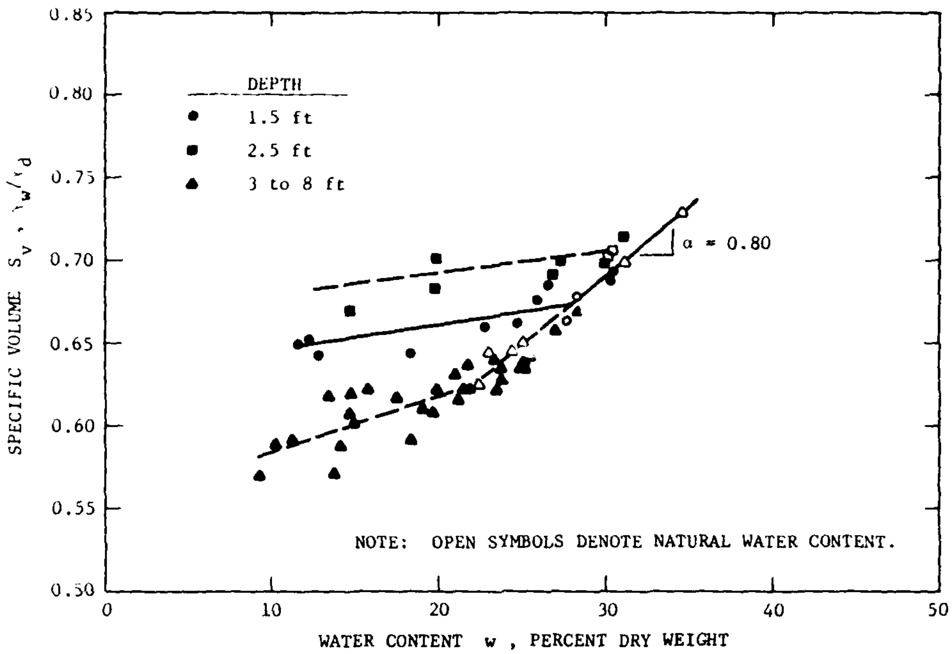
Information on piezometric pore water pressures is used in approximating the matrix suction-water content relationship in the presence of appreciable osmotic suctions.

15. The matrix suction-water content relationship may be difficult to determine accurately if an appreciable osmotic suction exists. The matrix suction-water content relationship shown in Figure A4 was approximated by noting that the groundwater elevation, in which $u_w = 0$, was 1.5 ft. Hence, the matrix suction at the natural water content of 27 percent was the confining pressure σ_m of 0.1 tsf from Equation A1. The remainder of the curve was approximated by subtracting 26 tsf which was the total mean suction at the natural water content of 27 percent less 0.1 tsf, from the total soil suction observed at lesser water contents. The osmotic suction should be subtracted from the total suction; otherwise, heave predictions will be overestimated if Equation 6 or 7 (paragraph 49) is used to estimate the final pore water pressure profile.

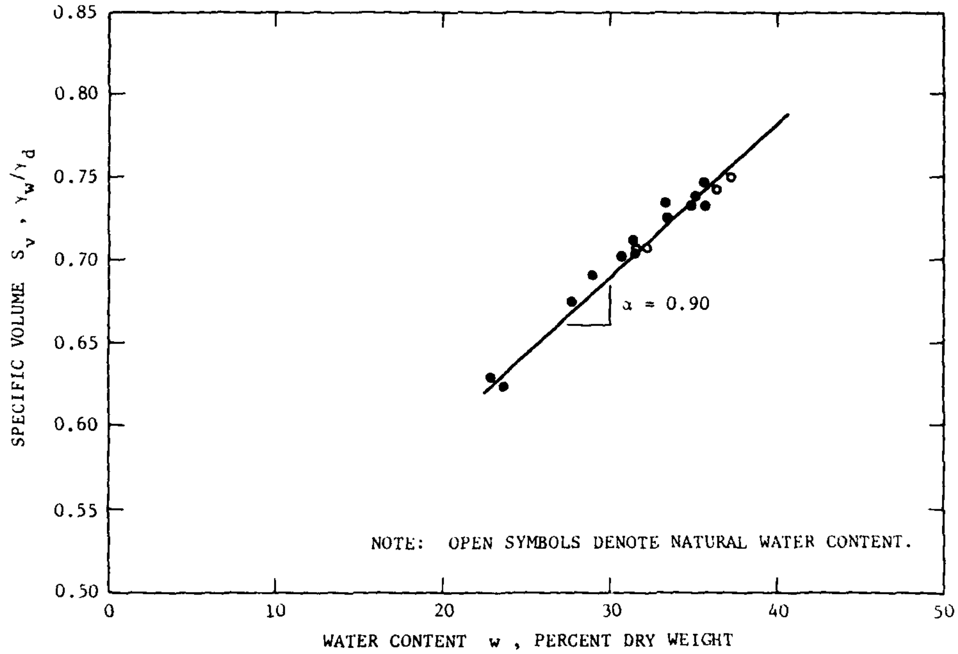
Compressibility factor

16. The compressibility factor α is the ratio of the change in specific volume S_v for a corresponding change in water content; i.e., the slope of the curve γ_w/γ_d plotted as a function of the water content, where γ_w is the unit weight of water and γ_d is the dry density. Highly plastic soils commonly have α close to one, while sandy and low-plasticity soils commonly have α values much less than one. High compressibility factors can indicate highly swelling soils. However, soils with all voids filled with water also have α values equal to one.

APPENDIX B: COMPRESSIBILITY FACTORS

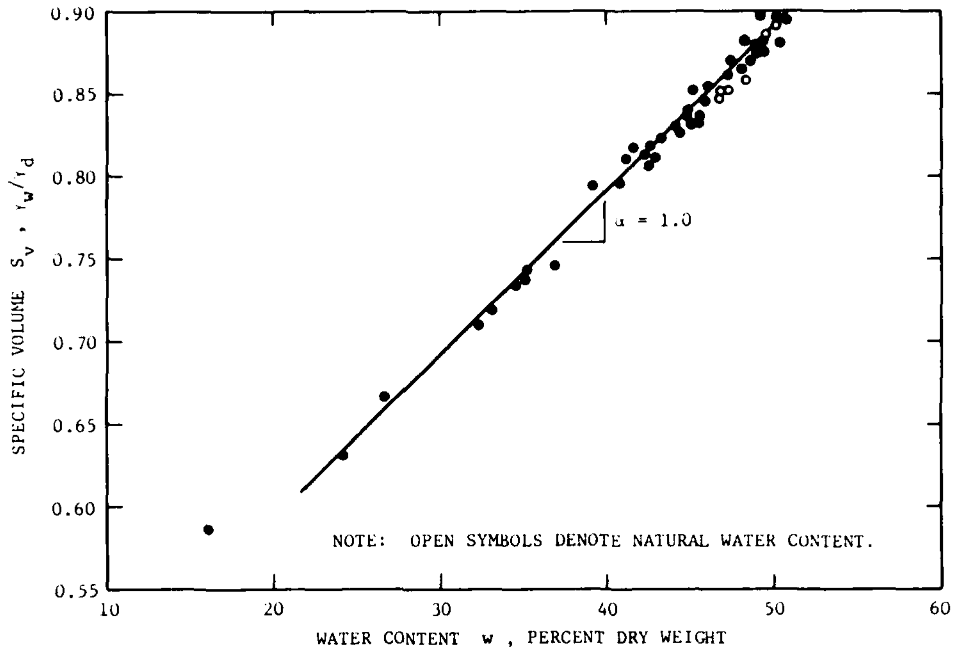


a. 1.0 to 8.0 ft

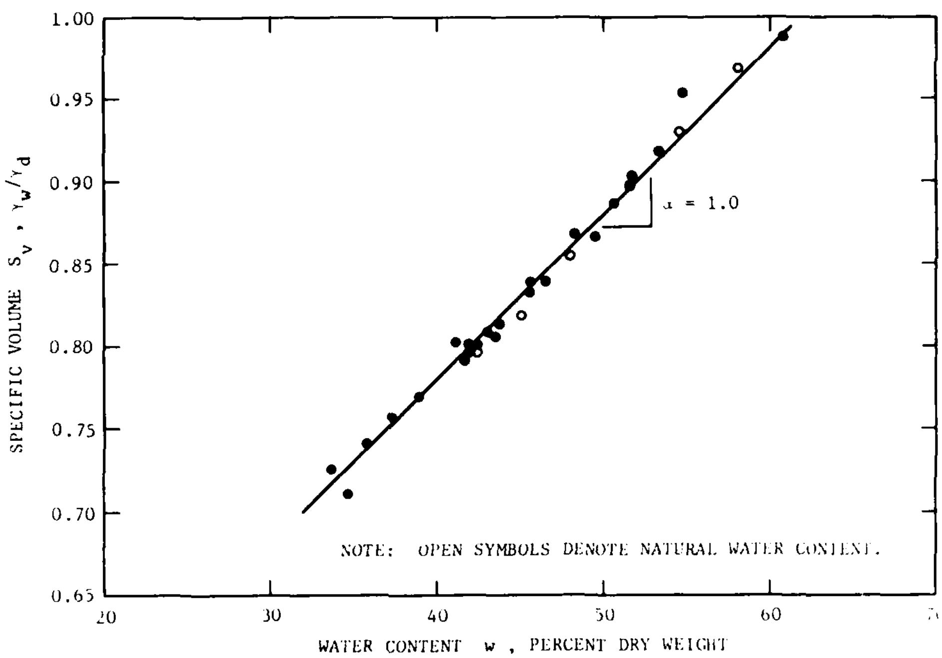


b. 8.0 to 11.0 ft

Figure B1. Compressibility factors for Clinton soil (sheet 1 of 3)

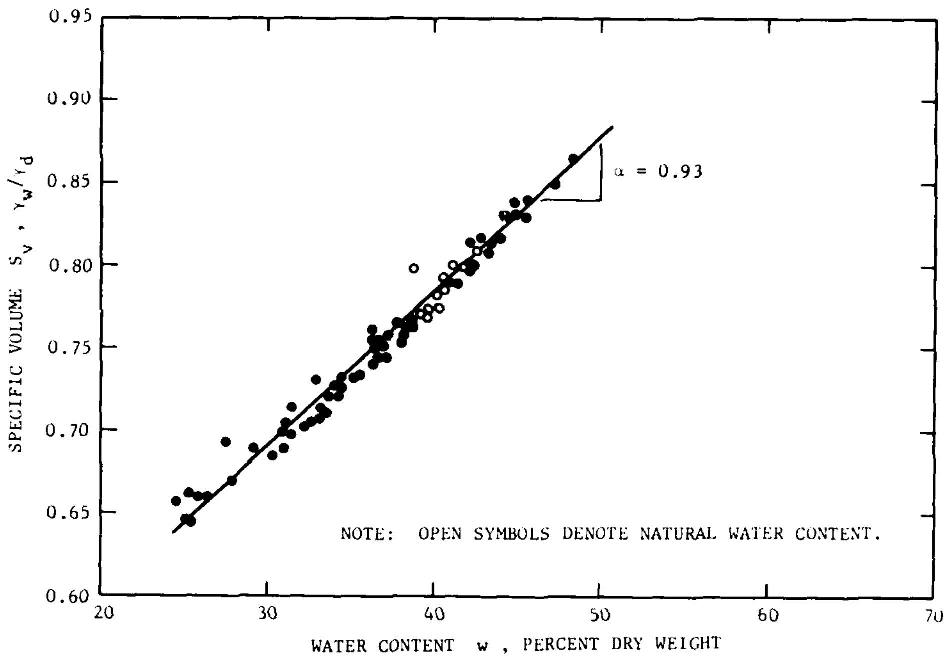


c. 11.0 to 21.0 ft



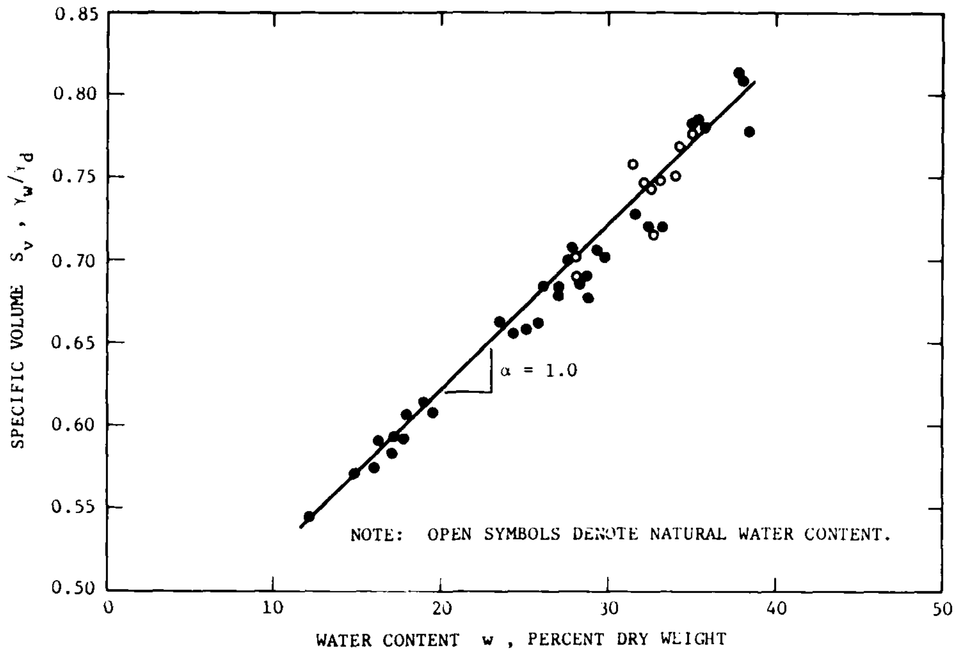
d. 21.0 to 25.0 ft

Figure B1. (sheet 2 of 3)

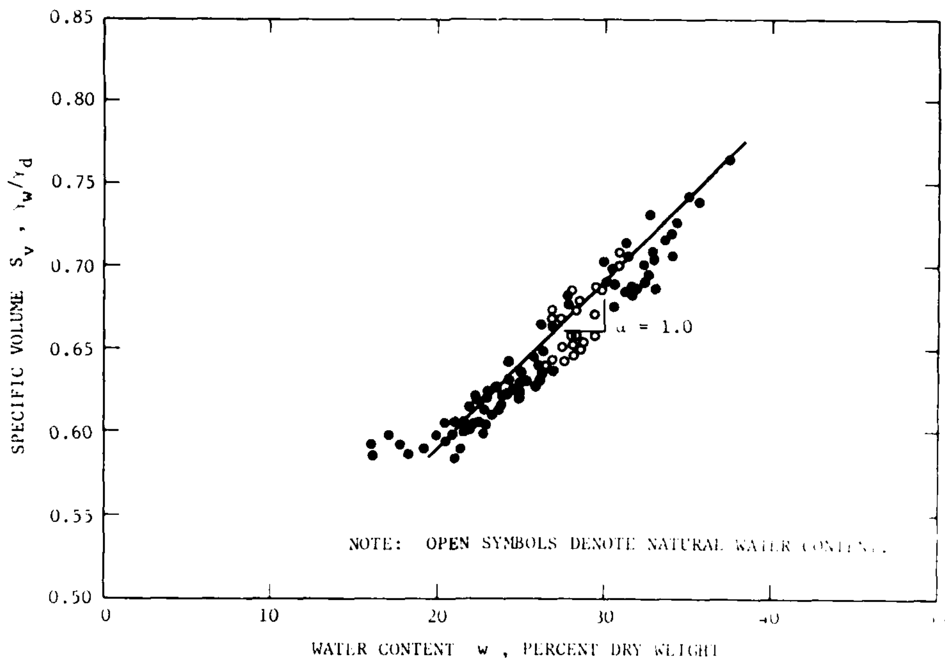


e. 25.0 to 50.0 ft

Figure B1. (sheet 3 of 3)

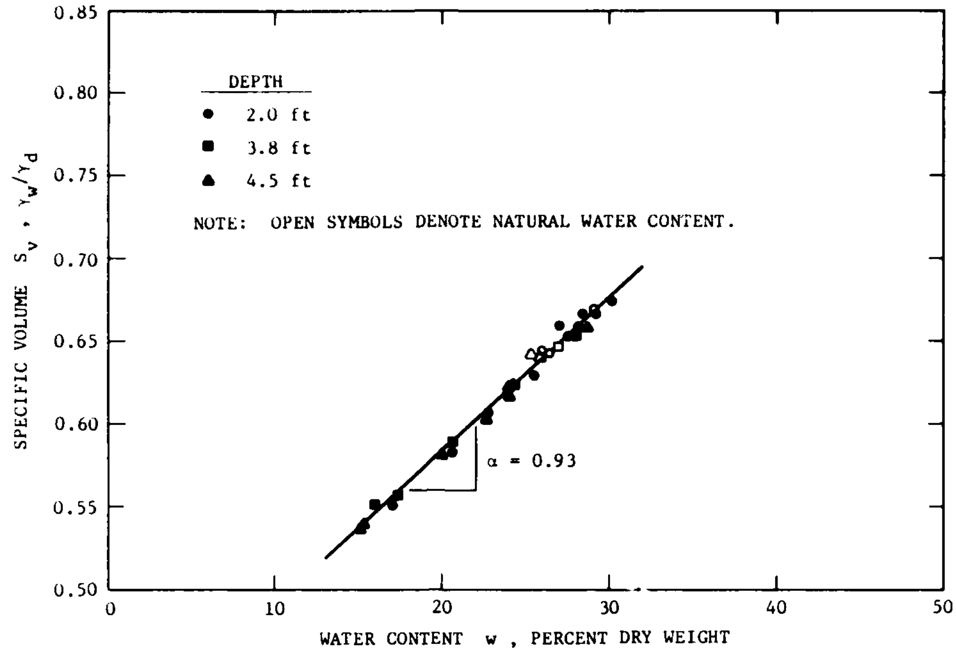


a. 1.0 to 8.0 ft

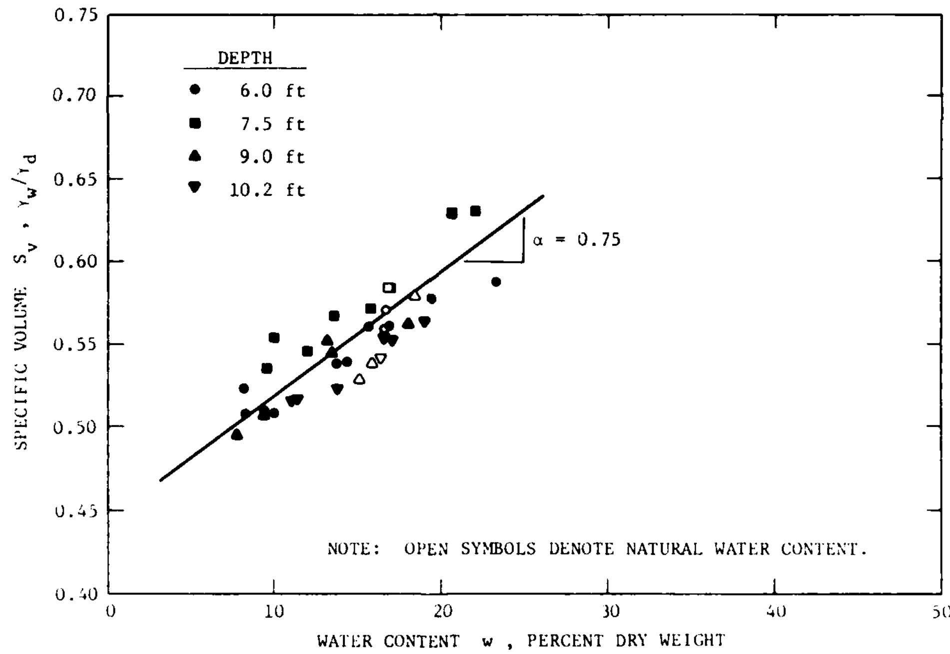


b. 20.0 to 50.0 ft

Figure B2. Compressibility factors for Lackland soil

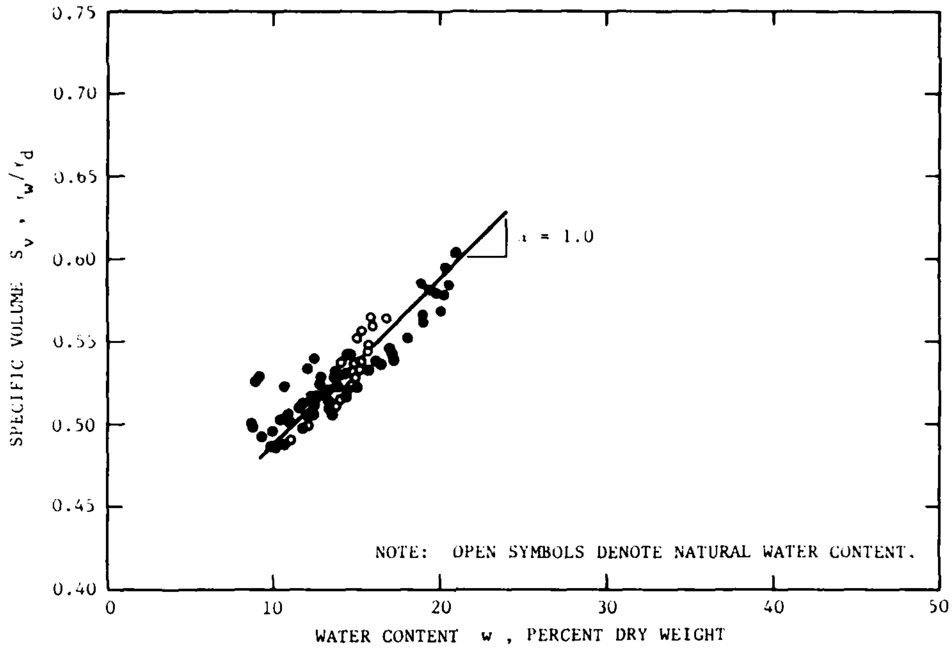


a. 1.0 to 5.0 ft

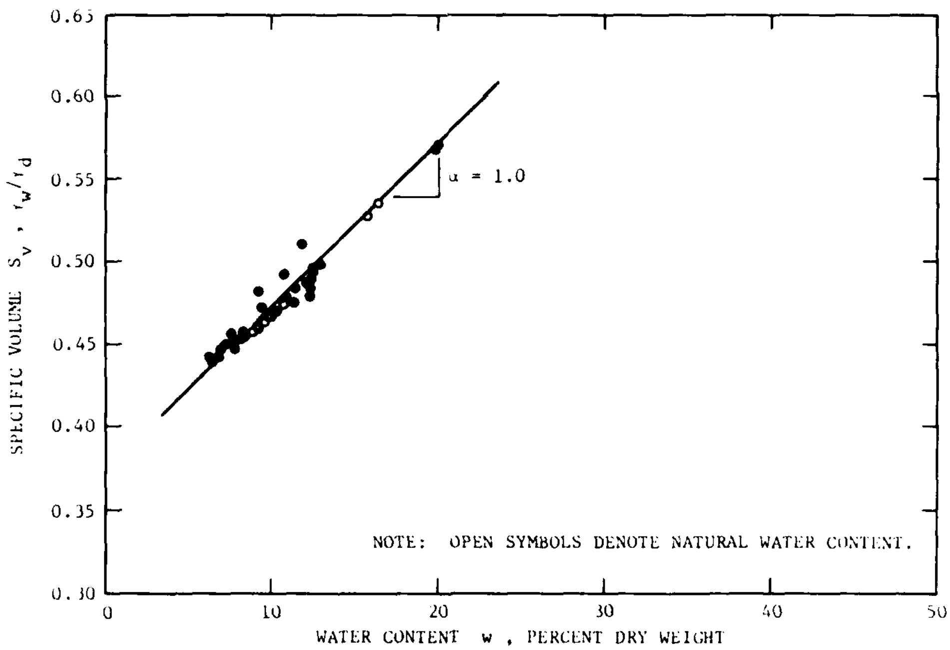


b. 5.0 to 11.0 ft

Figure B3. Compressibility factors for Fort Carson soil (sheet 1 of 2)



c. 11.0 to 25.0 ft



d. 25.0 to 50.0 ft

Figure B3. (sheet 2 of 2)

APPENDIX C: SOIL SUCTION-WATER CONTENT RELATIONSHIPS FOR CLINTON SOIL

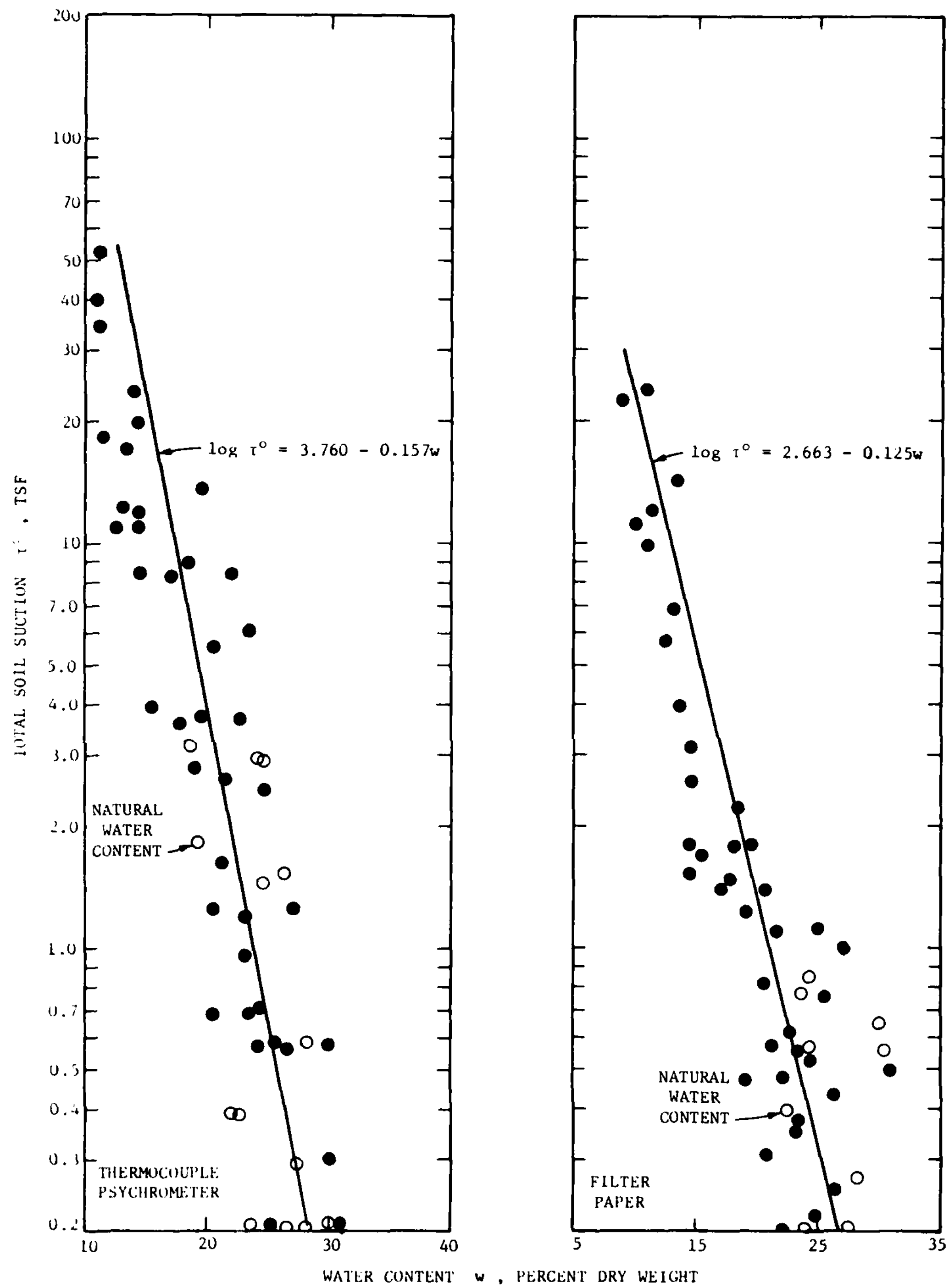


Figure C1. Soil suction-water content relationships for Clinton soil, 1.0- to 8.0-ft depth

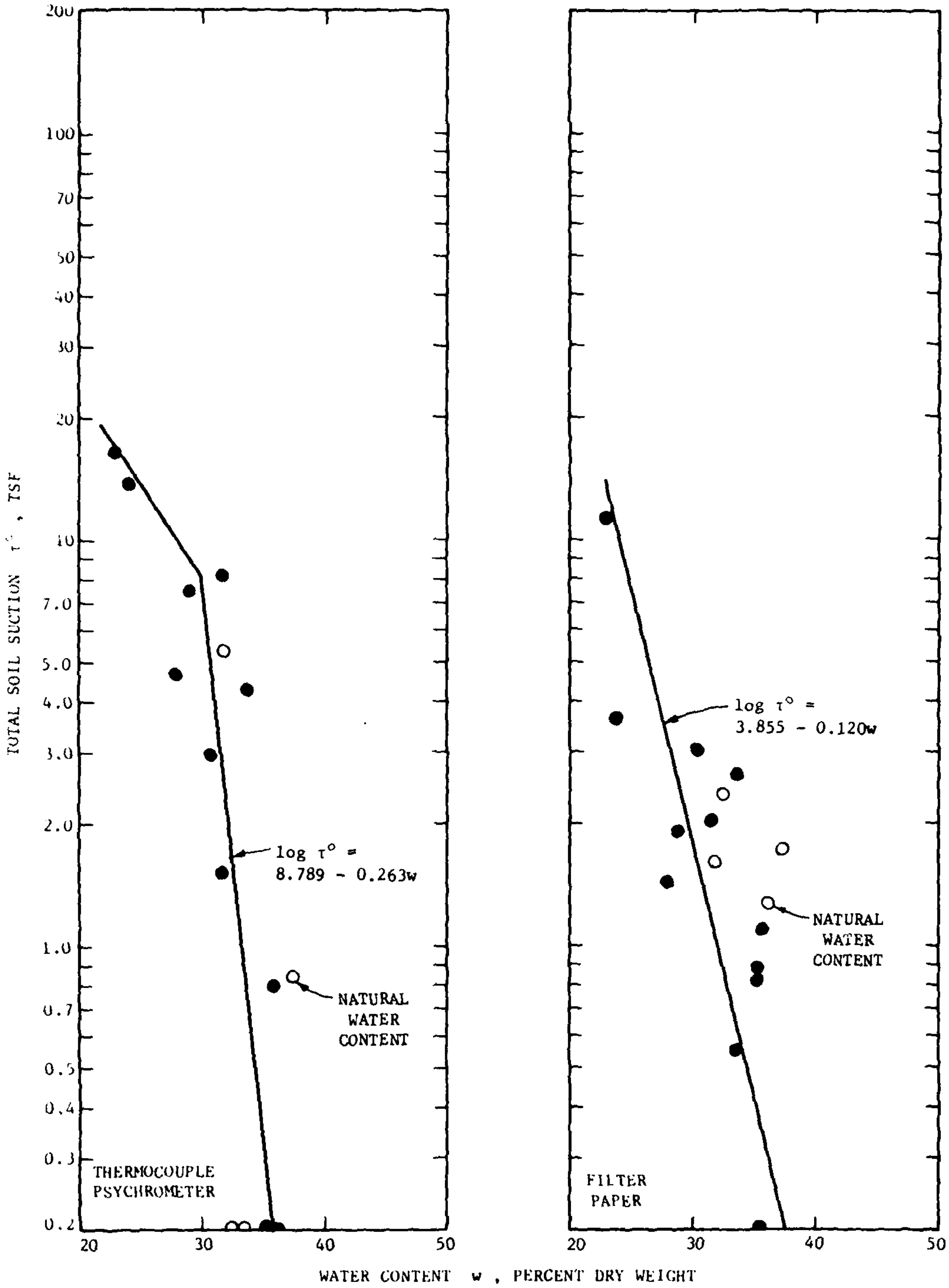


Figure C2. Soil suction-water content relationships for Clinton soil, 8.0- to 11.0-ft depth

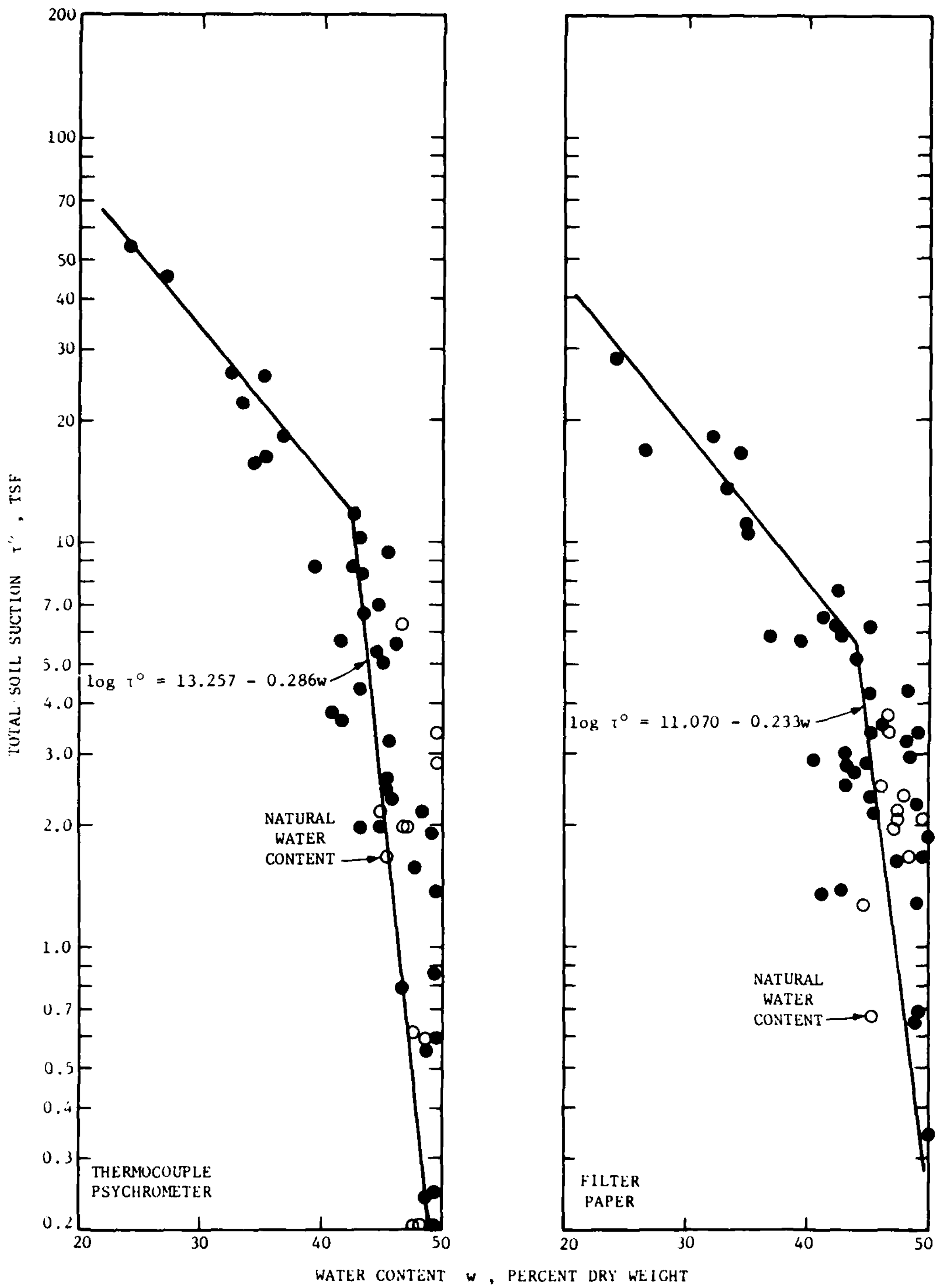


Figure C3. Soil suction-water content relationships for Clinton soil, 11.0- to 21.0-ft depth

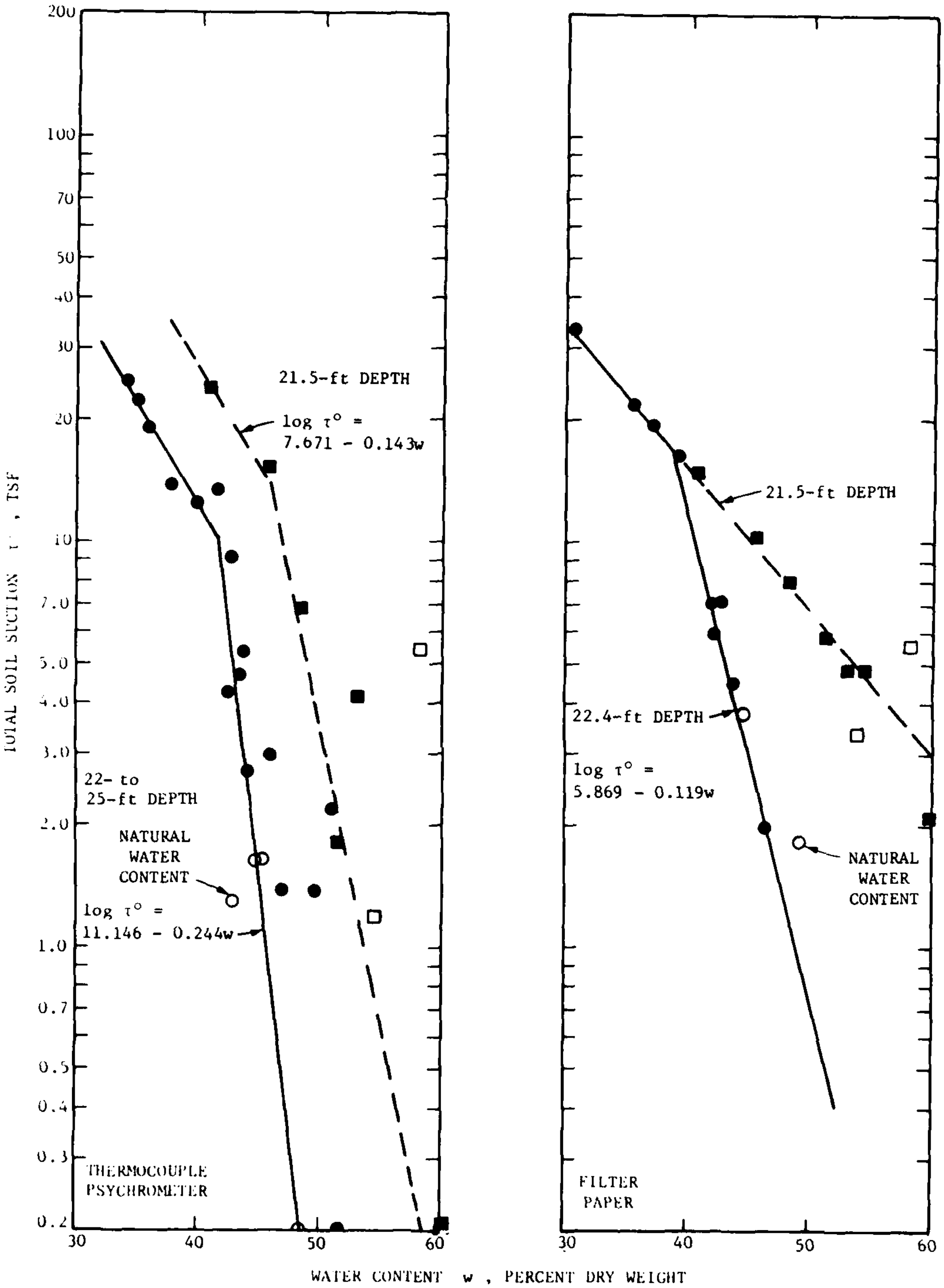


Figure C4. Soil suction-water content relationships for Clinton soil, 21.0- to 25.0-ft depth

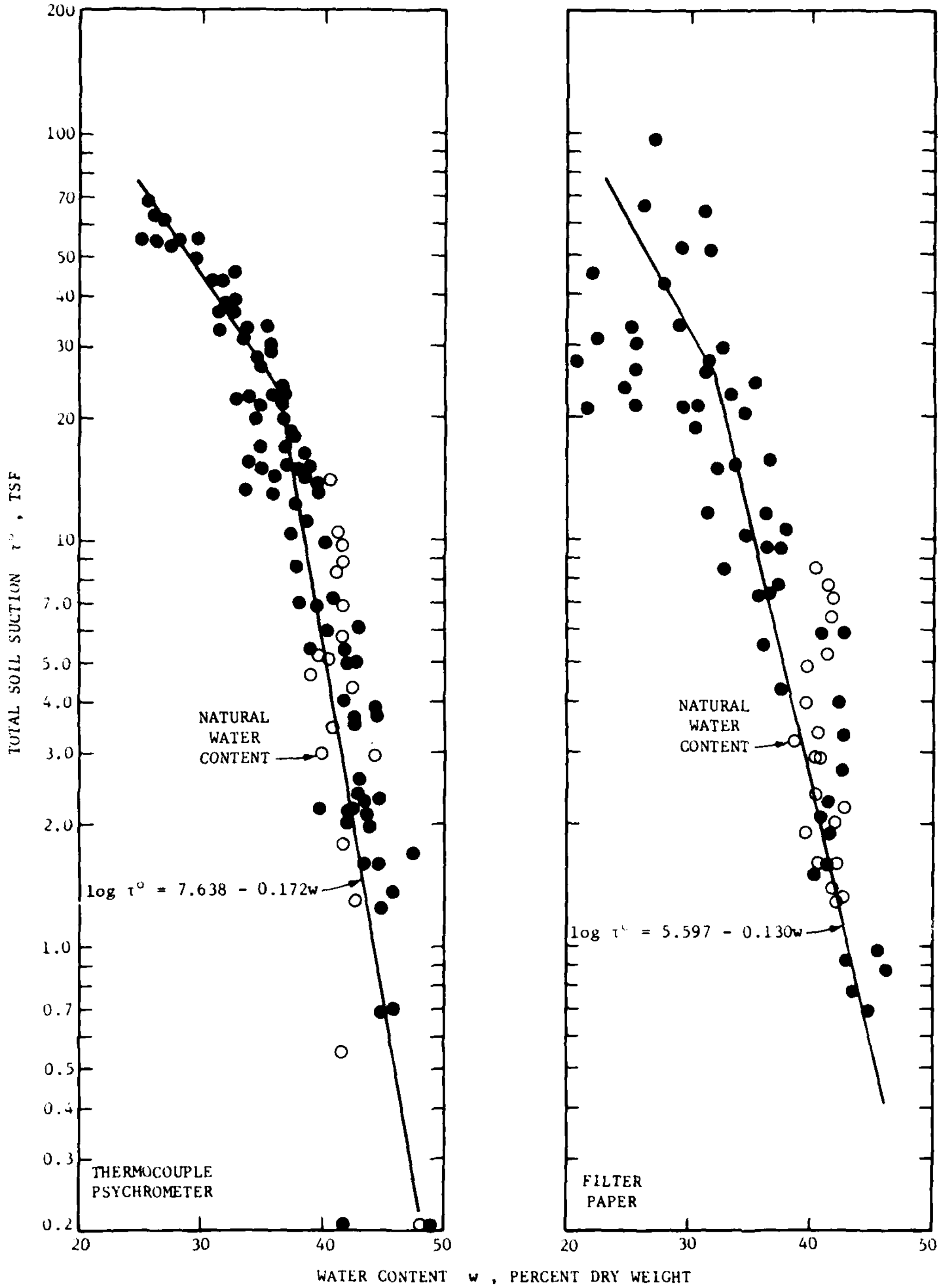


Figure C5. Soil suction-water content relationships for Clinton soil, 25.0- to 50.0-ft depth

APPENDIX D: SOIL SUCTION-WATER CONTENT RELATIONSHIPS FOR LACKLAND SOIL

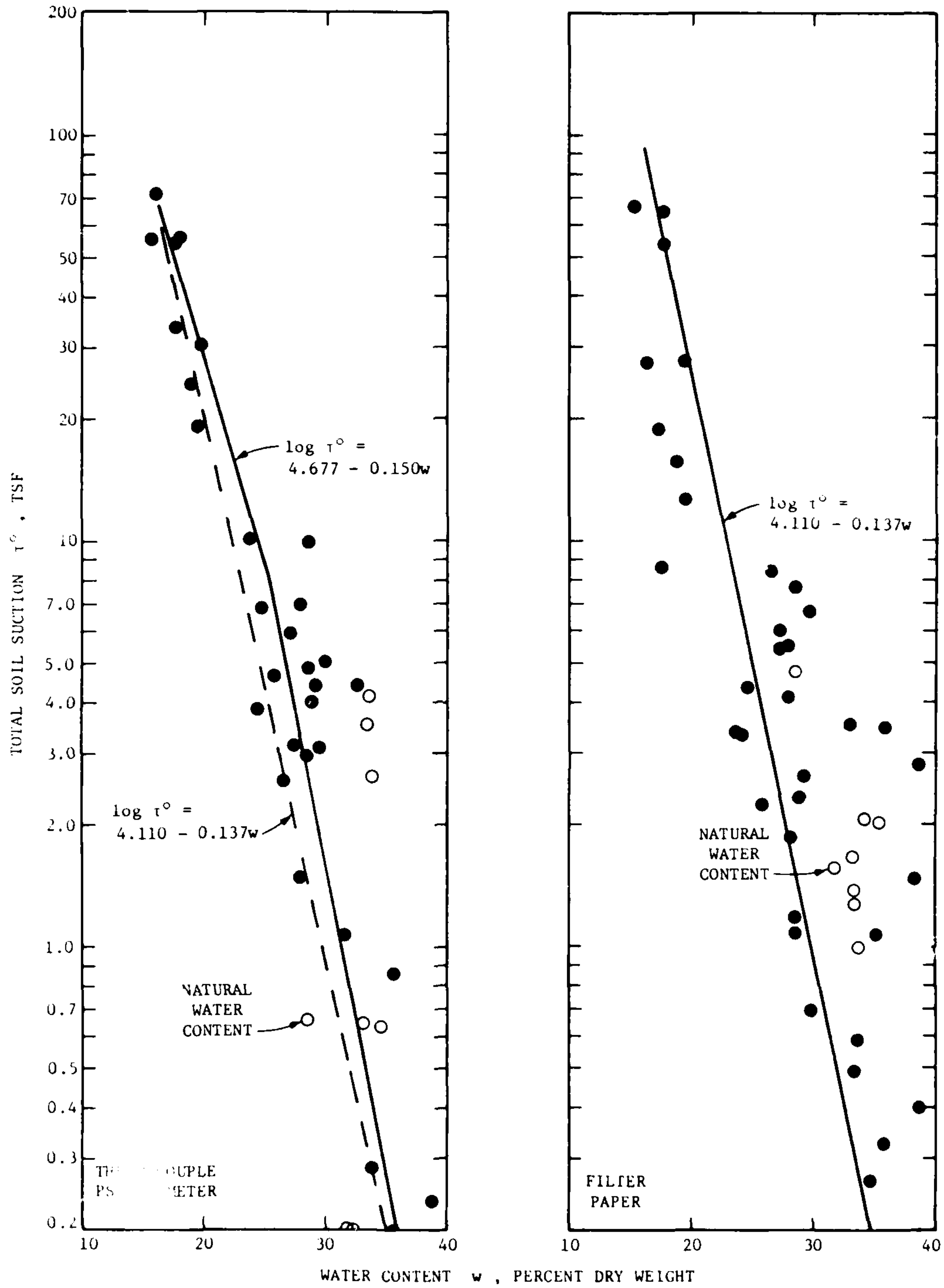


Figure D1. Soil suction-water content relationships for Lackland soil, 1.0- to 8.0-ft depth

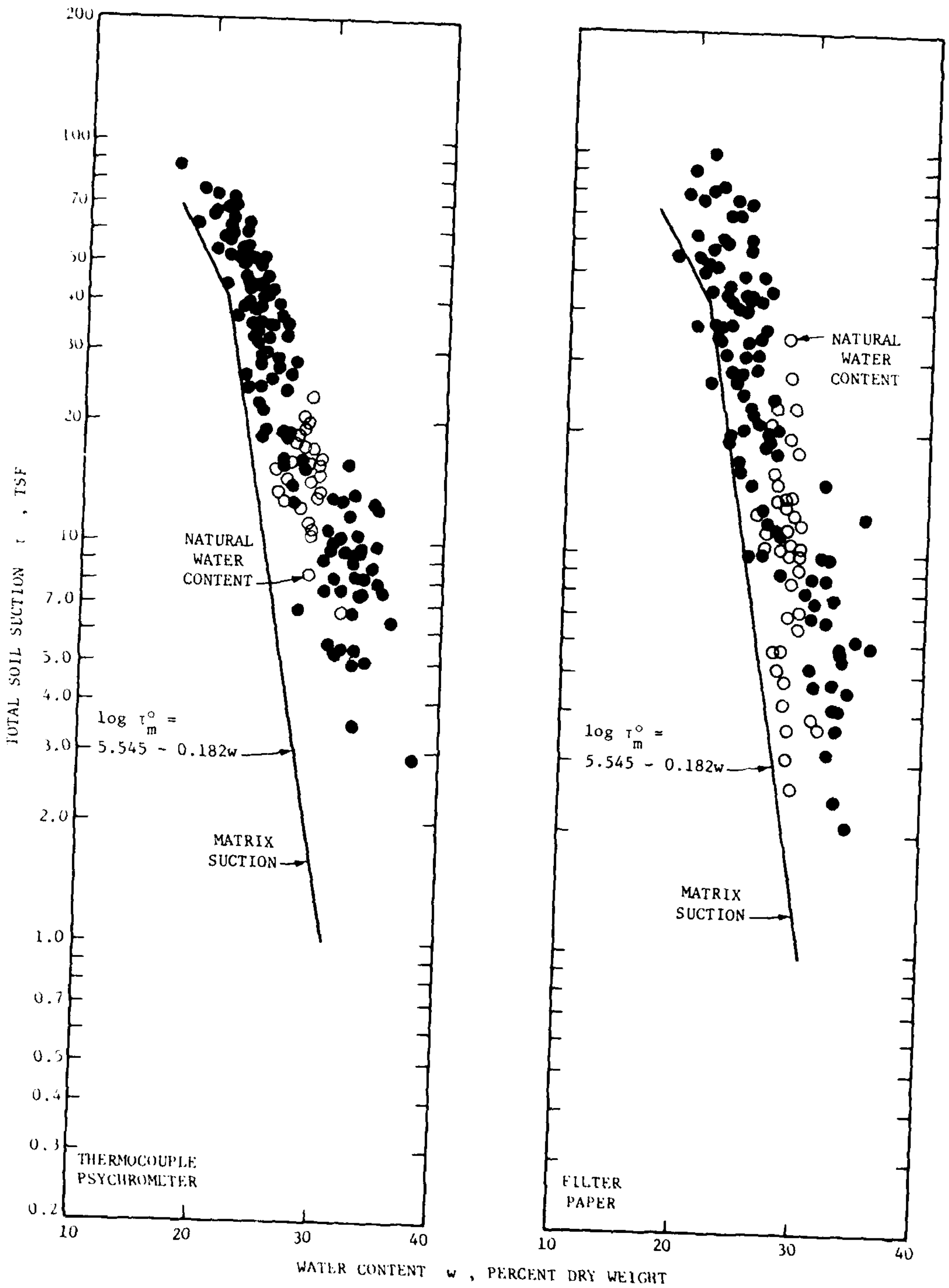


Figure D2. Soil suction-water content relationships for Lackland soil, 20.0- to 50.0-ft depth

APPENDIX E: SOIL SUCTION-WATER CONTENT RELATIONSHIPS FOR FORT CARSON SOIL

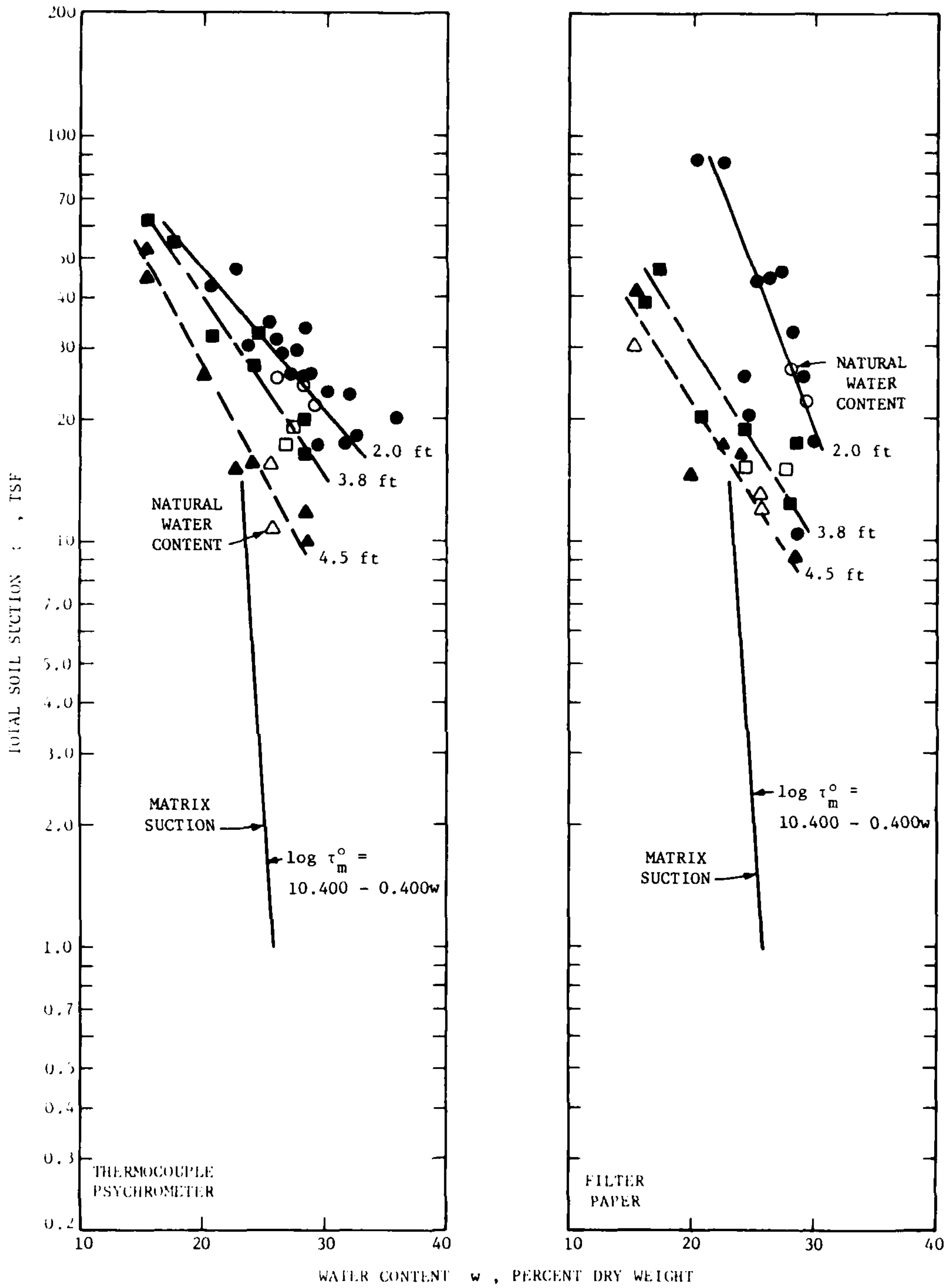


Figure E1. Soil suction-water content relationships for Fort Carson soil, 1.0- to 5.0-ft depth

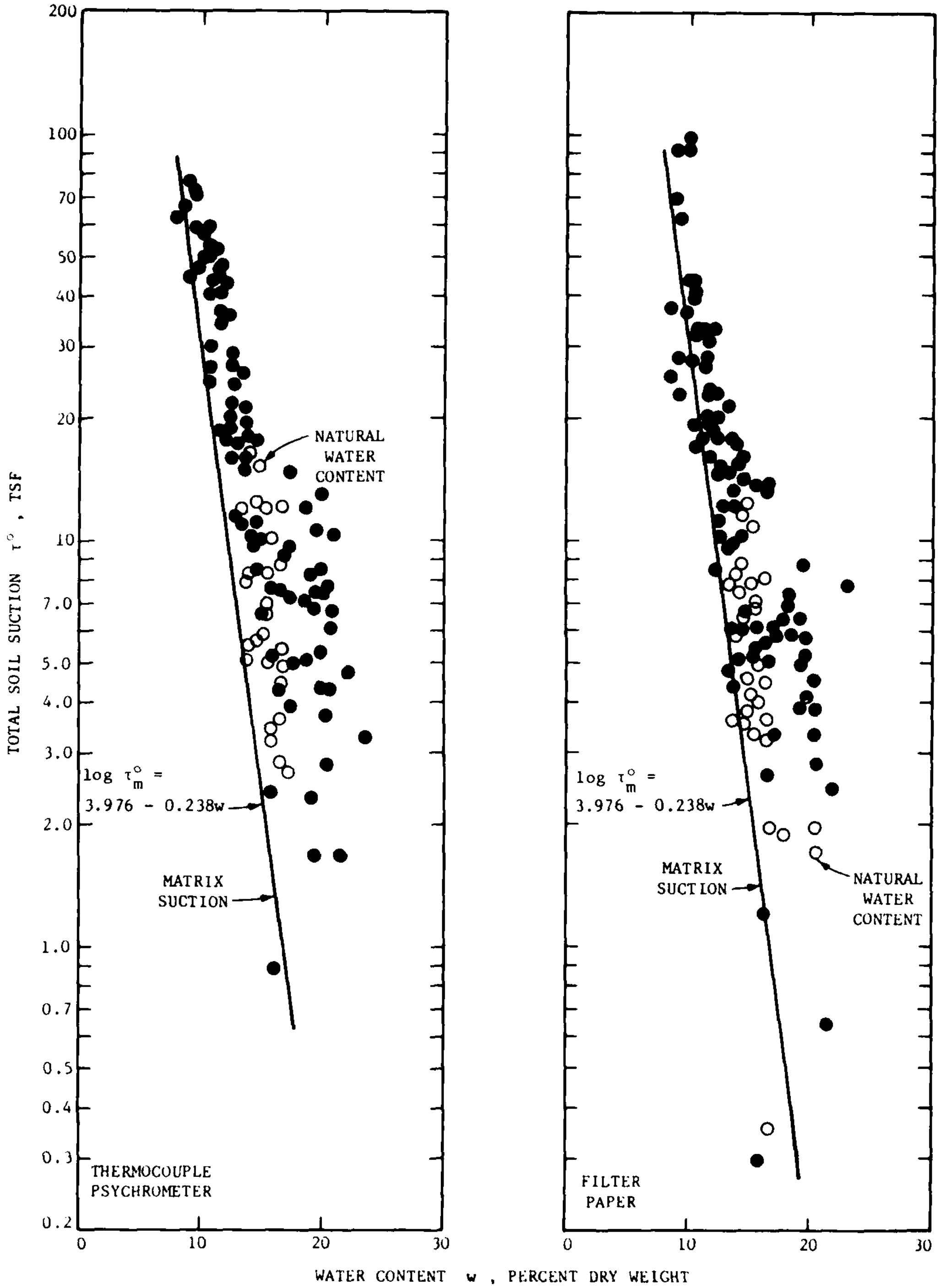


Figure E2. Soil suction-water content relationships for Fort Carson soil, 5.0- to 25.0-ft and 28.0- to 29.0-ft depths

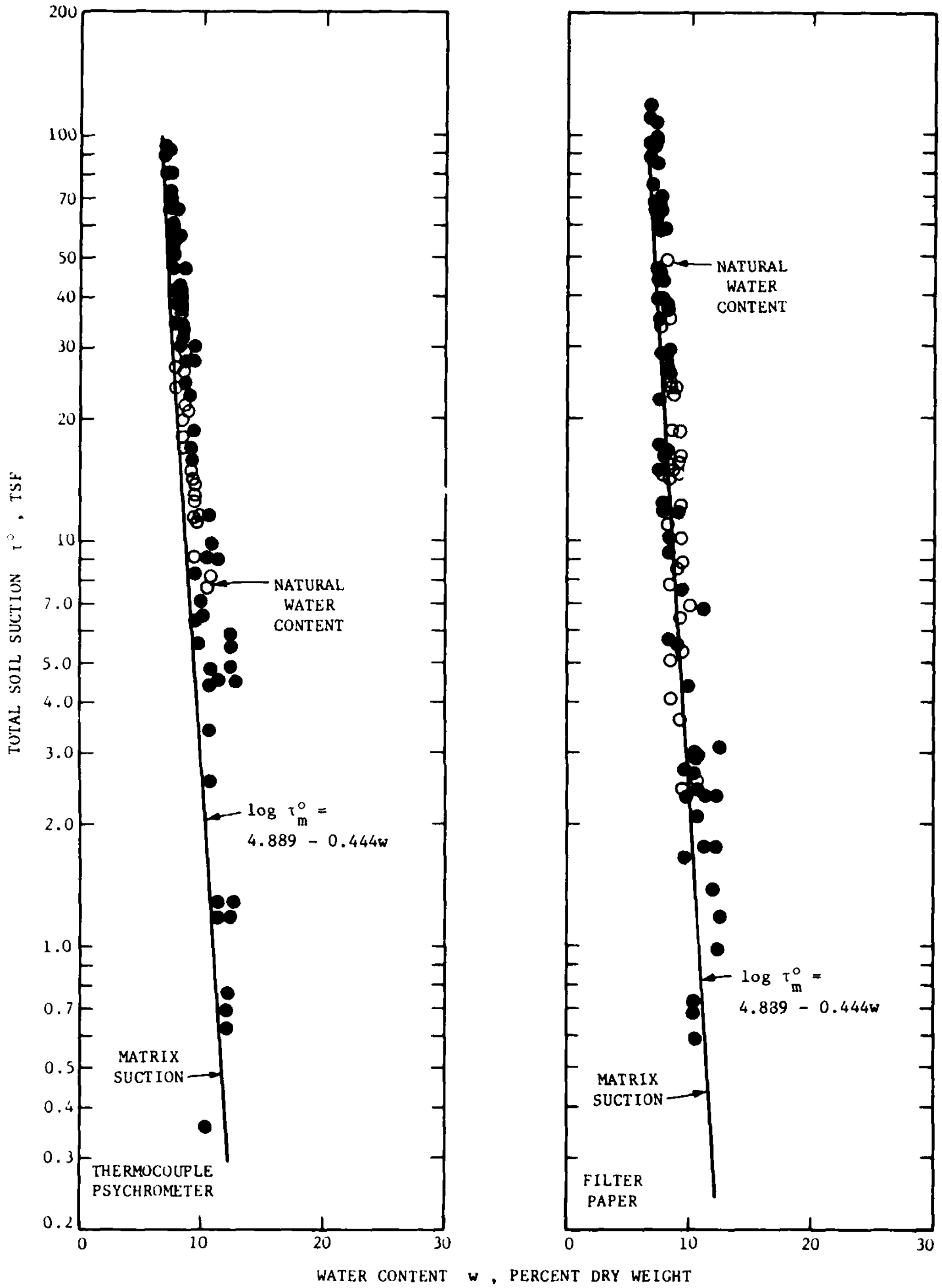


Figure E3. Soil suction-water content relationships for Fort Carson soil, 25.0- to 50.0-ft depth (except 28.0 to 29.0 ft)

APPENDIX F: NOTATION

a	Empirical constant that is a function of the heat index I
A	Ordinate intercept of the soil suction-water content curve
B	Slope of the soil suction-water content curve
C	Amount of water stored in the soil, in.
C_f	Field water capacity of the soil, in.
d	Monthly water deficiency, in.
D	Annual water deficiency, in.
DELTA(i)	Potential volumetric swell of soil element i , fraction
DX	Increment of depth, ft
e_o	Initial void ratio
$e_o(i)$	Initial void ratio of element i
$e_f(i)$	Final void ratio of element i
E_{25}	Microvolts at 25°C
E_t	Microvolts at t°C
G_s	Specific gravity
H	Depth to initial water table
i	Monthly heat index, soil element
I	Annual heat index
K_T	Ratio of total horizontal to vertical stress in situ
M	Amount of available water in the soil, in.
MI	Thornthwaite moisture index
N	Fraction of volumetric swell that occurs as heave in the vertical direction
NEL	Total number of elements
NBX	Number of nodal point at the bottom of the foundation
pe	Monthly potential evapotranspiration, in.
PE	Annual potential evapotranspiration, in.
p	Pressure of water vapor, tsf
p_o	Pressure of saturated water vapor, tsf
p/p_o	Relative humidity
r	Monthly rainfall
R	Ideal gas constant (86.82 cc-tsf/K-mole)

s	Monthly water surplus, in.
S	Annual water surplus, in.
S_v	Specific volume
T	Absolute temperature, K
t	Temperature, °C
u_w	Pore water pressure at depth X, tsf
u_{wa}	Pore water pressure at depth of the active zone X_a, tsf
v	Volume of a mole of liquid water (18.02 cc/mole)
w	Water content, percent
w_o	Initial water content, percent
X	Depth, ft
X_a	Depth of the active zone, ft
α	Compressibility factor
γ_d	Dry density, tons/ft^3
γ_w	Unit weight of water, 0.0312 ton/ft^3
ΔH	Potential heave at the bottom of the foundation, ft
σ_m	Mean normal confining pressure, tsf
σ_v	Total vertical pressure, tsf
τ°	Total soil suction without surcharge except atmospheric pressure, tsf
τ_m°	Matrix suction without surcharge except atmospheric pressure, tsf
τ_s	Osmotic suction, tsf

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Johnson, Lawrence D.
Field test sections on expansive soil : final report / by Lawrence D. Johnson (Geotechnical Laboratory, U.S. Army Engineer Waterways Experiment Station.) -- Vicksburg, Miss. : The Station, 1981.
86 p. in various pagings : ill. ; 27 cm. -- (Technical report / U.S. Army Engineer Waterways Experiment Station ; GL-81-4.)
Cover title.
"Prepared for Office, Chief of Engineers, U.S. Army, under RDT&E Work Unit AT40/EO/004."
"Available from National Technical Information Service, Springfield, Va. 22151."
Bibliography: p. 53-54.
1. Field investigations. 2. Soil mechanics. 3. Swelling soils. I. United States. Army. Corps of Engineers. Office of the Chief of Engineers. II. United States. Army Engineer Waterways Experiment Station. Geotechnical Laboratory. III. Title IV. Series: Technical report (United States. Army Engineer Waterways Experiment Station) ; GL-81-4.
TA7.W34 no.GL-81-4

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